Test of the universality of τ and μ lepton couplings in W-boson decays with the ATLAS detector

Article (Published Version)

nature physics

ARTICLES

https://doi.org/10.1038/s41567-021-01236-w

Check for updates

OPEN

Test of the universality of τ and μ lepton couplings in W-boson decays with the ATLAS detector

ATLAS Collaboration*

The standard model of particle physics encapsulates our best current understanding of physics at the smallest scales. A fundamental axiom of this theory is the universality of the couplings of the different generations of leptons to the electroweak gauge bosons. The measurement of the ratio of the decay rate of W bosons to τ leptons and muons, $R(\tau/\mu)$, constitutes an important test of this axiom. Using 139 fb^{-1} of proton–proton collisions recorded with the ATLAS detector at a centre-of-mass energy of 13 TeV, we report a measurement of this quantity from di-leptonic $t\bar{t}$ events where the top quarks decay into a W boson and a bottom quark. We can distinguish muons originating from W bosons and those originating from an intermediate τ lepton through the muon transverse impact parameter and differences in the muon transverse momentum spectra. The measured value of $R(\tau/\mu)$ is 0.992 ± 0.013 [± 0.007(stat) ± 0.011(syst)] and is in agreement with the hypothesis of universal lepton couplings as postulated in the standard model. This is the only such measurement from the Large Hadron Collider, so far, and obtains twice the precision of previous measurements.

It is a fundamental axiom of the standard model (SM) that the couplings of the electroweak gauge bosons (W, Z) to charged leptons, g_ℓ (ℓ = electron (e), muon (μ), tau (τ)), are independent of the mass of the leptons. This fundamental assumption is referred to as 'lepton-flavour universality' and is tested in this Article by comparing the relative decay rates, or branching ratios (B), of on-shell W bosons to τ leptons and muons, by measuring the ratio $R(\tau/\mu) = B(W \to \tau\nu_\tau)/B(W \to \mu\nu_\mu)$.

The measurement exploits the large number of top and anti-top quark pair ($t\bar{t}$) events produced in proton–proton (pp) collisions at the Large Hadron Collider (LHC). Given that $B(t \to Wq)$ is close to 100%, this gives a very large sample of W-boson pairs. These are used to obtain a large sample of clean and unbiased W-boson decays to muons and τ leptons. The τ leptons are identified through their decay to muons. The τ lepton has a significant lifetime[1,2] compared to the W boson and undergoes a multi-body decay to a muon and neutrinos. This leaves two distinctive signatures in the detector, the displacement of the τ decay vertex and, on average, a lower muon transverse momentum (p_{T}). These features are used to distinguish between muons from the $W \to \tau\nu_\tau \to \mu\nu_\mu\nu_\tau\nu_\tau$ and $W \to \mu\nu_\mu$ processes, to extract $R(\tau/\mu)$. The precision of the measurement relies on the highly accurate reconstruction of muon tracks obtainable by the ATLAS experiment.

Previously, $R(\tau/\mu)$ has been measured at the Large Electron–Positron Collider (LEP), yielding a combined value of 1.070 ± 0.026 (ref. [3]). The SM expectation of $R(\tau/\mu)$ is unity (neglecting very small phase space effects due to the masses of the decay products, $\sim 5 \times 10^{-4}$)[4], which differs from the measured value, motivating a precise measurement of this ratio at the LHC. Other experimental measurements of the ratio $B(W \to \tau\nu_\tau)/B(W \to \ell\nu_\ell)$, where ℓ is either an electron or a muon, have not yet reached the precision of the LEP results[5–9]. The equivalent ratio for the two light generations, $B(W \to \mu\nu_\mu)/B(W \to e\nu_e)$, has been accurately measured by the LEP[3], LHCb[10] and ATLAS[11] experiments, and is found to be consistent with the SM prediction at the 1% level. Additionally, although most low-energy experiments[12] show good agreement, to very high precision, with the hypothesis of universality of lepton couplings, recent results from LHCb[13–16], Belle[17–19] and BaBar[20,21] show some tension with the SM, further motivating this analysis.

This measurement relies on precise knowledge of the branching ratio of τ leptons decaying to muons to extrapolate to the full $W \to \tau\nu_\tau$ branching ratio. The value of (17.39 ± 0.04)%, measured by the LEP experiments[4,22–25], is used in the analysis.

Experimental set-up

The ATLAS experiment[26–28] at the LHC is a multipurpose particle detector with nearly hermetic coverage for recording particles produced in LHC collisions through a combination of particle position and energy measurements. ATLAS has a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle. More details of the ATLAS coordinate system are provided in the Methods. ATLAS consists of an inner tracking detector surrounded by a thin superconducting solenoid providing an axial magnetic field of 2 T, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors, and the innermost layer of the pixel detector is at a radius of 33 mm from the beamline, providing a precise measurement of track impact parameters. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions of the detector are instrumented with LAr calorimeters for both electromagnetic and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large air-core toroidal superconducting magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate of 100 kHz. This is followed by a software-based trigger that reduces

*A list of authors and their affiliations appears online.

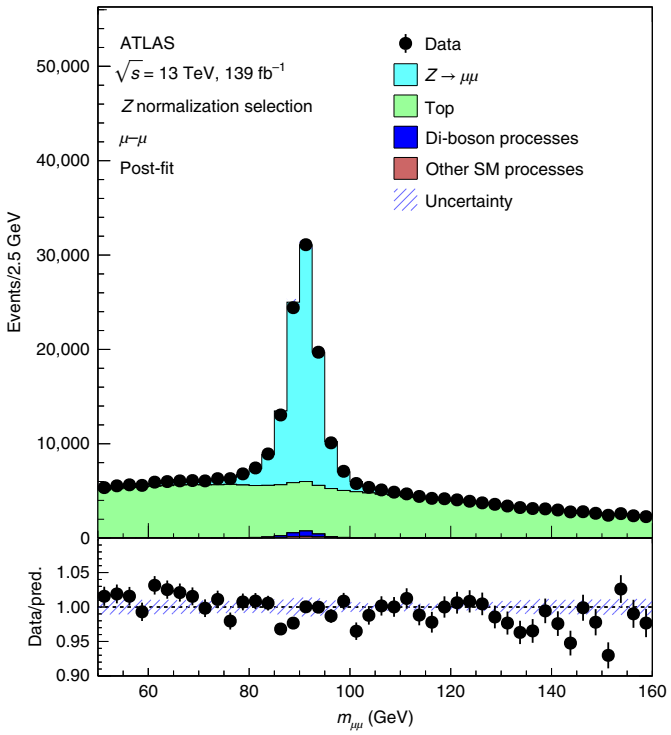

Fig. 1 | $Z \to \mu\mu$ background normalization. A region enriched in $Z \to \mu\mu$ events is defined by selecting events with two muons. This control region is used to extract the $Z \to \mu\mu$ normalization, which is applied in the signal region. A histogram with a fixed bin width of 2.5 GeV of the di-muon invariant mass ($m_{\mu\mu}$) distribution is shown in the figure. The data are shown by black markers and the different components contributing to this region, taken from simulation, are shown by stacked histograms. The different contributions are the primary process of interest ($Z \to \mu\mu$), along with the main backgrounds from events involving top quarks (Top), a pair of W and/or Z bosons (Di-boson processes) and the grouping of all remaining SM processes (Other SM processes). The bottom panel shows the ratio of the data to the predicted expectation after the fit. The uncertainties on the data are the Poisson errors due to the limited size of the data sample. Blue bands indicate the $\pm 1\sigma$ systematic uncertainties on the prediction, with the constraints from the analysis fit applied.

the accepted event rate to 1 kHz, on average, depending on the data-taking conditions.

The analysed pp collision data were recorded with the ATLAS detector from 2015 to 2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. Owing to the conditions required to achieve high instantaneous luminosity, in these data there are additional collisions in the same and neighbouring LHC proton bunch crossings (pile-up). This resulted in an average of 34 collisions per bunch crossing.

Events in this measurement were selected by single-lepton triggers[29–31] requiring a single high-p_{T} isolated electron or muon. After the application of data-quality requirements[32], the data sample corresponds to an integrated luminosity of 139 fb^{-1} with an uncertainty of 1.7%[33], obtained using the LUCID-2 detector[34] for the primary luminosity measurements.

Samples of simulated events were produced using Monte Carlo techniques to model the different SM processes. After event generation of the process of interest for each sample, the detector response was modelled using a simulation based on GEANT4[35]. The data and Monte Carlo simulated events were passed through the same reconstruction and analysis procedures. Samples were simulated for the signal processes, the production of $t\bar{t}$ and single top quarks in association with a W boson (Wt), as well as the different backgrounds. Precise details of the theoretical predictions and event generators used to create the simulated events are provided in the Methods.

Selecting a pure and unbiased sample of W bosons

Collisions are selected to obtain a high-purity sample of $t\bar{t}$ events in which the top quarks decay into a W boson and a b quark, and the two W bosons then decay to leptons. This is referred to as di-leptonic $t\bar{t}$. The two leptonic W-boson decays are exploited in a tag and probe approach: in each event, tag leptons (electrons or muons) are used to select the event, after which a test is performed to determine, in an unbiased way, whether the probe muon was directly produced by a W boson, $W \to \mu\nu_{\mu}$, or via an intermediate τ lepton, $W \to \tau\nu_{\tau} \to \mu\nu_{\mu}\nu_{\tau}\nu_{\tau}$. Events are categorized into signal regions, used to extract $R(\tau/\mu)$, and additional control regions, used to constrain the normalization of the major backgrounds.

The selections rely on reconstructed muons, electrons and hadronic jets. Details of the physics object reconstruction definitions used are provided in the Methods. Events entering the signal region are required to contain either one electron and one muon of opposite electric charge (e–μ channel) or two muons of opposite electric charge (μ–μ channel). In the e–μ channel, the electron is required to pass the trigger, and in the μ–μ channel, the tag muon is required to pass the trigger. This ensures that the probe muons have no trigger bias. If both leptons in the μ–μ channel satisfy the tag and probe criteria, both muons in turn are used as probes. Events with more than two leptons are rejected. In addition, events must have at least two reconstructed hadronic jets that are identified as containing a b hadron. Finally, to reduce the backgrounds from Z bosons and hadron decays, events where the invariant mass of the two muons, $m_{\mu\mu}$, satisfies $85 < m_{\mu\mu} < 95$ GeV are excluded in the μ–μ channel, and events with di-lepton mass $m_{\ell\ell} < 15$ GeV are excluded in both channels.

This selection results in a sample of approximately half a million collision events, with a di-leptonic $t\bar{t}$ purity of over 95% in the e–μ channel and 85% in the μ–μ channel. This sample is used to test the origin of the probe muons and extract the measurement of $R(\tau/\mu)$. This is extracted from the ratio of the number of events in which the probe muon orginates from the process $W \to \tau\nu_{\tau} \to \mu\nu_{\mu}\nu_{\tau}\nu_{\tau}$, referred to as $\mu_{\tau(\to\mu)}$, to those that come from the process $W \to \mu\nu_{\mu}$, referred to as μ_{prompt}. A fit is performed that exploits the difference in shape between these two components and the backgrounds of the distributions of the probe muon's transverse impact parameter $|d_0^{\mu}|$ and its transverse momentum p_{T}^{μ}.

Muon transverse impact parameter distribution calibration

The muon's transverse impact parameter $|d_0^{\mu}|$ has particular importance for this analysis and requires careful treatment. It is measured in the x–y plane as the closest distance of approach of the track to the beamline. The shape of the $|d_0^{\mu}|$ distribution of prompt muons is determined using a $Z \to \mu\mu$ calibration region to create templates that are used to predict the distribution in the signal region.

The calibration region is defined by requiring that two muons satisfying the same kinematic criteria as in the signal region, but with the di-muon mass requirement changed to $85 < m_{\mu\mu} < 100$ GeV. No requirements on hadronic jets are applied. This gives a sample of ~95 million prompt muons with a purity of >99.9%.

Templates of the shape of the $|d_0^{\mu}|$ distribution are then taken from this data sample after subtracting the expected contributions from the simulation of processes with significant muon parent lifetimes, primarily $Z \to \tau\tau$. These $|d_0^{\mu}|$ templates are extracted in 33 bins in p_{T}^{μ} and $|\eta^{\mu}|$ to capture the dependence of the distribution on these variables. Separate templates are used for 2015 + 2016, 2017 and 2018 data to account for differences in the beam conditions and in the alignment of the inner detector.

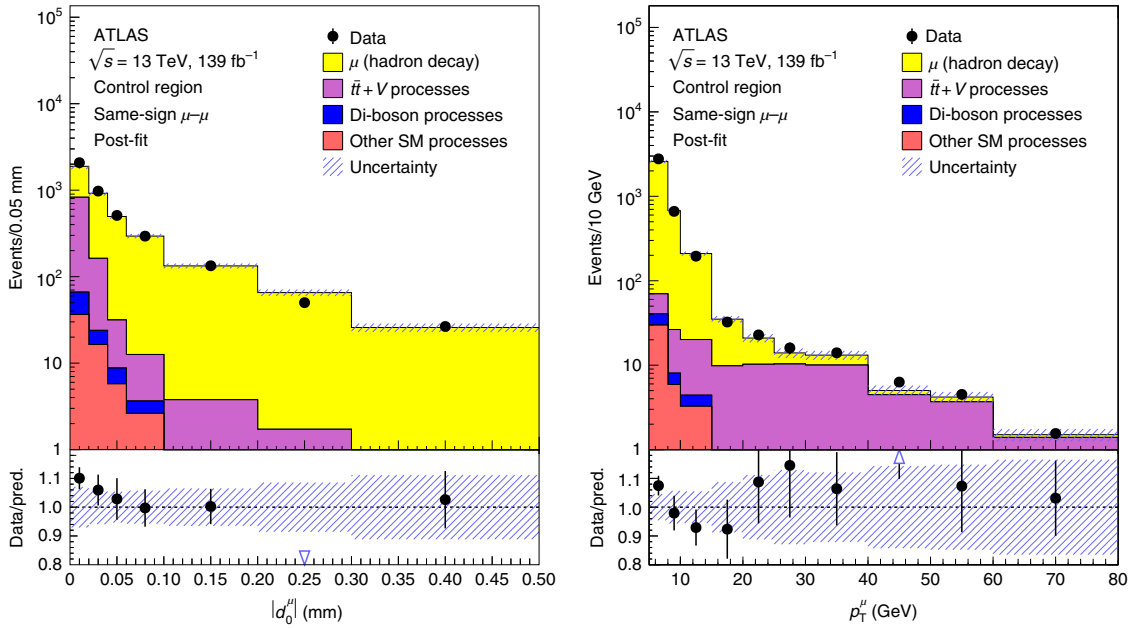

Fig. 2 | μ_{had} background normalization. A region enriched in μ_{had} events is defined by selecting events with two same-sign muons. This control region is used to extract normalization factors to correct the μ_{had} prediction to match the data. The probe muon tranverse impact parameter (left, $|d_0^{\mu}|$) and transverse momentum (right, p_{T}^{μ}) distributions in this region are shown. The data are shown by black markers and the different components contributing to this region, taken from simulation, are shown by stacked histograms. The different contributions are the primary process of interest, μ_{had} (μ (hadron decay)), along with the main backgrounds from events involving a top quark pair produced in association with a W or Z boson ($t\bar{t}+V$ processes), a pair of W and/or Z bosons (Di-boson processes) and the grouping of all remaining SM processes (Other SM processes). The y-axis label includes the value that defines the scaling of the variable bin width histogram. The extracted normalization factor is applied to the μ_{had} prediction, along with the effect of any constraints and pulls on the systematic uncertainties from the fit to the signal region data. The bottom panels show the ratio of the data to the predicted expectation after the fit. The uncertainties on the data are the Poisson errors due to the limited size of the data sample. Blue bands indicate the $\pm 1\sigma$ systematic uncertainties on the prediction with the constraints from the analysis fit applied. The open blue arrowheads in the ratio panel indicate points where the ratio values lie outside the y-axis range shown.

Additionally, using this calibration region, the Gaussian part of the $|d_0^{\mu}|$ resolution is estimated in data and simulation by fitting the $|d_0^{\mu}|$ distribution in the range $|d_0^{\mu}| < 0.02$ mm. For $p_{\text{T}}^{\mu} = 20$ GeV, the resolution is ~14 μm. Corrections to account for differences in the resolution of the detector between the data and simulation are applied to the muons from τ decays and hadron decays. For the range of $|d_0^{\mu}|$ values considered in this analysis, $|d_0^{\mu}| < 0.5$ mm, the resolution measured from prompt muons is applicable to those with significant displacement.

Background normalization estimation

The two largest backgrounds are $Z(\rightarrow\mu\mu)$ + jets and events in which the probe muon does not originate from a W-boson decay. Three dedicated control regions are used to extract the normalization of these backgrounds.

The $Z(\rightarrow\mu\mu)$ + jets background is important at small values of $|d_0^{\mu}|$. The normalization of the $Z(\rightarrow\mu\mu)$ + jets background in the μ–μ channel is extracted from the data in a control region where the same event selection is applied, including the hadronic jet requirements, but without the $m_{\mu\mu}$ criterion, and is then extrapolated to the signal region using simulation. In the control region, the peak of the invariant mass distribution of the di-muon system is fitted over the range $50 < m_{\mu\mu} < 140$ GeV. A Voigt profile[36] is used for the $Z \rightarrow \mu\mu$ resonance and a third-order Chebychev polynomial for all non-resonant processes, which provides a good description of the data. Other functions were tested to provide a systematic uncertainty, which is combined with the statistical uncertainties. The normalization factor required to scale the simulated sample to data is found to be 1.36 ± 0.01. The di-muon invariant mass in the control region is shown in Fig. 1 after this normalization is applied. This normalization factor is also applied to the small $Z(\rightarrow\tau\tau)$ + jets background.

The most important background at large values of $|d_0^{\mu}|$ is from events in which the probe muon originates from the decay of b or c hadrons, or more rarely from in-flight decays of $\pi^{\pm}$ and $K^{\pm}$. This occurs primarily in $t\bar{t}$ events where one W boson decays leptonically and the other hadronically, referred to as semi-leptonic $t\bar{t}$. These muons are referred to as μ_{had}. A data-driven method is used to determine the normalization of this background from two control regions, one each for the e–μ and μ–μ channels. The control regions have the same event selection as the signal regions, but the two leptons are required to have same-sign electric charge. This results in a sample with a high purity of this μ_{had} background.The largest source of μ_{had} is from decays of b hadrons, and this contributes equally to same-sign and opposite-sign selections, while the other substantial source, c hadrons, has a component in both selections, but they are not equal. The extrapolation from same-sign control region to opposite-sign signal region is estimated from simulation. In the same-sign control region there are two backgrounds to μ_{had} at high p_{T}^{μ}: $t\bar{t}+V$, and $t\bar{t}$, which occurs through electron charge misidentification in the e–μ channel. A normalization correction factor is applied to these processes based on the number of events observed with a probe muon with $p_{\text{T}}^{\mu} > 30$ GeV. This is done before extracting the normalization of the μ_{had} background. The normalization factors to scale the simulation to data for the μ_{had} background are found to be 1.39 and 1.37 in the e–μ and μ–μ, channels, respectively. Figure 2 shows that the simulation and data are consistent within uncertainties in the μ–μ channel same-sign control region, providing confidence that the differential distributions of p_{T}^{μ} and $|d_0^{\mu}|$ are well-modelled.

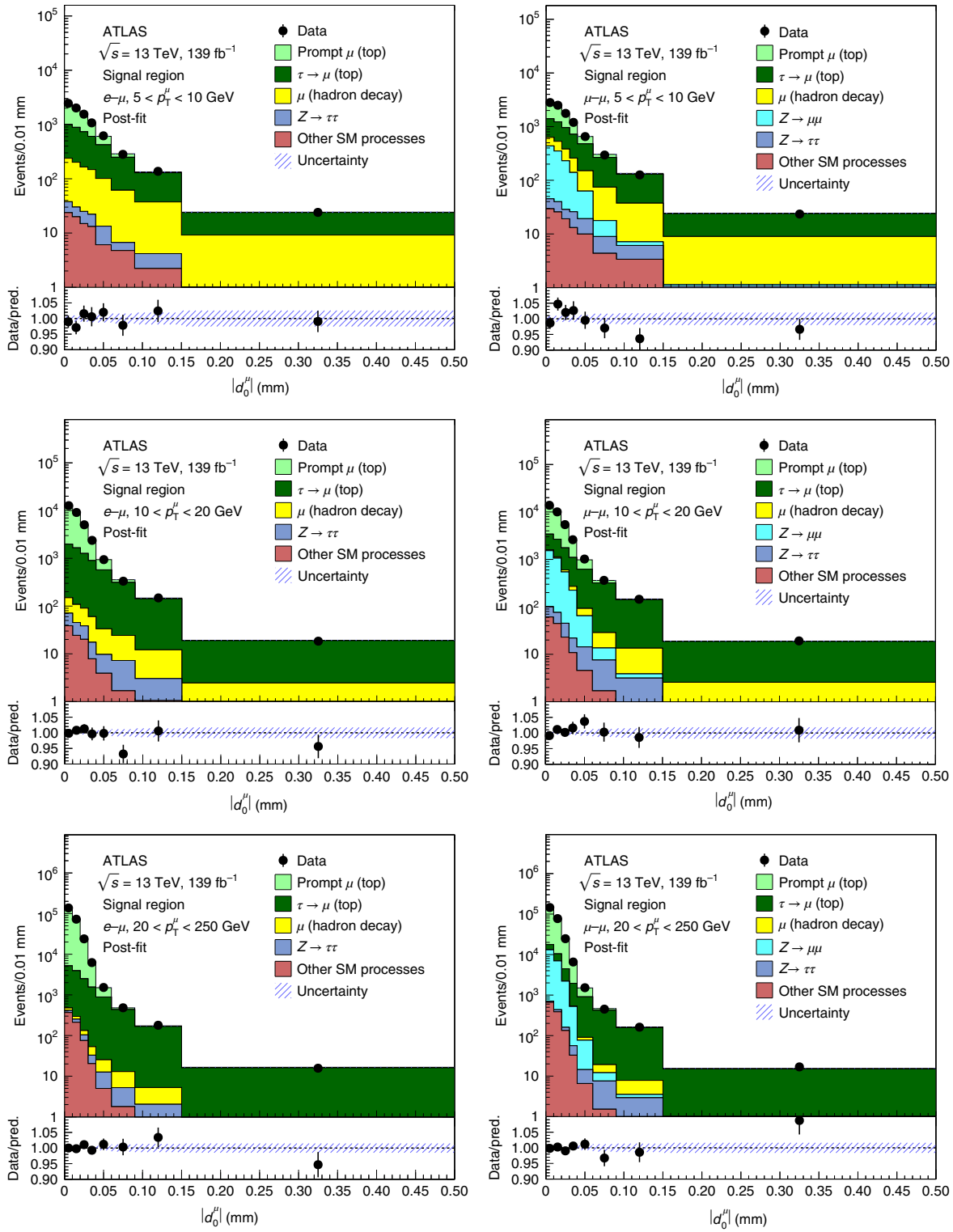

Fig. 3 | Transverse impact parameter distributions of probe muons in the signal region. The signal region used to extract $R(\tau/\mu)$ is enriched in di-lepton $t\bar{t}$ events. The $|d_0^\mu|$ distributions for each signal region (left, e–μ channel; right, μ–μ channel) and probe muon p_T^μ bin (top, 5 < p_T^μ < 10 GeV; middle, 10 < p_T^μ < 20 GeV; bottom, 20 < p_T^μ < 250 GeV) used in the analysis are shown. The data are represented by black markers and the different components contributing to this region, taken from simulation, are shown by stacked histograms. The different contributions are the two primary processes of interest used to extract $R(\tau/\mu)$, μ_{prompt} from top quark decays (Prompt μ (top)) and $\mu_{\tau(\to\mu)}$ from top decays ($\tau \to \mu$(top)). The main backgrounds are also shown: events with a μ_{had} (μ (hadron decay)), events with a Z boson decaying to a di-muon pair ($Z \to \mu\mu$), events with a Z boson decaying to a di-τ pair ($Z \to \tau\tau$) and the grouping of all remaining SM processes (Other SM processes). Distributions are shown after the fit has been performed. The y-axis label includes the value that defines the scaling of the variable bin width histogram. The bottom panels show the ratio of the data to the predicted expectation after the fit. The uncertainties on the data are the Poisson errors due to the limited size of the data sample. Blue bands indicate the $\pm 1\sigma$ systematic uncertainties on the prediction with the constraints from the analysis fit applied. The contribution from 'Other SM processes' is dominated by di-boson and $t\bar{t} + V$ production. The chi-squared statistic values range from 3.5 to 10.2 for eight degrees of freedom for the distributions.

Table 1 | Sources of uncertainty

Source	Impact on $R(\tau/\mu)$
Prompt d_0^μ templates	0.0038
μ_{prompt} and $\mu_{\tau(\to\mu)}$ parton shower variations	0.0036
Muon isolation efficiency	0.0033
Muon identification and reconstruction	0.0030
μ_{had} normalization	0.0028
$t\bar{t}$ scale and matching variations	0.0027
Top p_{T} spectrum variation	0.0026
μ_{had} parton shower variations	0.0021
Monte Carlo statistics	0.0018
Pile-up	0.0017
$\mu_{\tau(\to\mu)}$ and μ_{had} d_0^μ shape	0.0017
Other detector systematic uncertainties	0.0016
Z+jet normalization	0.0009
Other sources	0.0004
$B(\tau\to\mu\nu_\tau\nu_\mu)$	0.0023
Total systematic uncertainty	0.0109
Data statistics	0.0072
Total	**0.013**

The main sources of uncertainty on the measured value of $R(\tau/\mu)$ are shown. The size of the impact each uncertainty has on $R(\tau/\mu)$ is assessed by fixing the relevant fit parameters for a given uncertainty and refitting to data. The reduction in the total uncertainty in this modified fit gives the quoted impact. Different individual components used in the fit are combined into categories.

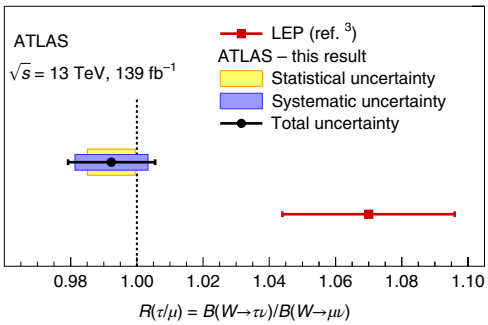

Fig. 4 | Summary of ATLAS and LEP results. The new ATLAS measurement of $R(\tau/\mu)$ and the previous LEP result[3] of the same quantity. The new measurement from ATLAS is shown by the black filled circle and the LEP result by a red filled square. For the ATLAS result the statistical (yellow box) and systematic (blue box) errors are shown separately, along with the total error of the measurement (black bars). The total uncertainty on the LEP result is indicated by the red bars. The vertical dashed line indicates the prediction lepton-flavour universality of the SM, with equal W-boson branching ratios to different lepton flavours.

Fit configuration and systematic uncertainties

A two-dimensional profile likelihood fit[37] is performed in the $|d_0^\mu|$ and p_{T}^μ distributions. The bin boundaries were chosen to provide the best separation between the different μ_{prompt}, $\mu_{\tau(\to\mu)}$ and μ_{had} processes given the available data. This resulted in three bins in p_{T}^μ (boundaries of 5, 10, 20 and 250 GeV) and eight bins in the transverse impact parameter $|d_0^\mu|$ (boundaries of 0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15 and 0.5 mm), of the probe muon for both the e–μ and μ–μ channels, making 48 bins in total.

The ratio of the number of $\mu_{\tau(\to\mu)}$ events to the number μ_{prompt} is fitted by minimizing the negative log-likelihood, to measure $R(\tau/\mu)$. More than 100 (nuisance) parameter values representing the statistical and systematic uncertainties, which can be modified by the fit, are included. The relative uncertainty of 0.23% in the $\tau\to\mu\nu_\mu\nu_\tau$ branching ratio is also included in the measured value of $R(\tau/\mu)$ and is a subdominant component of the overall uncertainty. As both the $t\bar{t}$ and Wt processes contain two W bosons, both are treated as signal. Two fit parameters are allowed to float freely: $R(\tau/\mu)$ and $k(t\bar{t})$. The $k(t\bar{t})$ parameter is a constant scaling factor applied to the normalization of both the μ_{prompt} and $\mu_{\tau(\to\mu)}$ components of the signal, whereas $R(\tau/\mu)$ only affects the $\mu_{\tau(\to\mu)}$ components. Both are applied across all bins and in both channels. $R(\tau/\mu)$ is the parameter of interest and is not affected by the overall normalization scaling factors of the $t\bar{t}$ and Wt processes. The fit is performed after applying the normalization scaling factors derived in the control regions. Other processes are normalized to their theoretical cross-sections, taking into account the uncertainty in these predictions.

Because many systematic uncertainties are correlated between the μ_{prompt} and $\mu_{\tau(\to\mu)}$ templates, they cancel out in the $R(\tau/\mu)$ ratio, minimizing their impact on the precision of the result. These include uncertainties related to jet reconstruction, flavour tagging and trigger efficiencies. The remaining dominant uncertainties are the uncertainties in the data-driven methods, the theoretical modelling uncertainties and the reconstruction uncertainties; these are described in the following and further details are provided in the Methods.

An uncertainty associated with the data-driven templates for the $|d_0^\mu|$ distribution of μ_{prompt} is derived to account for the differences between the $Z\to\mu\mu$ calibration region where they were derived and the signal region.

Uncertainties in the data-driven normalization of the μ_{had} background due to the size of the same-sign dataset, the choice of Monte Carlo generators used and the uncertainty in the subtraction of the other processes in the same-sign control region are included in the fit. The uncertainties associated with the Z+jets normalization derived from data are also applied. Uncertainties on the cross-section calculations and the integrated luminosity are applied to all other backgrounds estimated from simulation, but have a minor impact on the result.

Uncertainties in the shape of the μ_{prompt}, $\mu_{\tau(\to\mu)}$ and μ_{had} distributions due to the modelling of the simulated $t\bar{t}$ samples are derived. The combined yield of the μ_{prompt} and $\mu_{\tau(\to\mu)}$ templates is allowed to float in the fit, but changes in generator configuration choices can result in modifications to the muon p_{T}^μ and subsequently the $|d_0^\mu|$ distribution, such that there can be relative changes in the μ_{prompt} and $\mu_{\tau(\to\mu)}$ template yields in each bin, leading to an uncertainty in $R(\tau/\mu)$. For the μ_{had} background, in addition to the uncertainties in the normalization, there can be changes to the muon p_{T}^μ modelling and the relative fractions of muons from different sources, both of which can change the shape of the $|d_0^\mu|$ distribution. The most important of these variations is in the parton shower and hadronization model.

The muon reconstruction and isolation efficiencies are determined in di-muon ($Z\to\mu\mu$ and $J/\psi\to\mu\mu$) data and simulation using a tag and probe method[38]. Corrections are applied to the simulated samples to account for the differences between data and simulation, and the uncertainties on these correction factors are included in the analysis. Additionally, an uncertainty due to the modelling of pile-up is obtained by reweighting the simulated events[39].

Extraction of $R(\tau/\mu)$

Figure 3 shows the differential distributions of $|d_0^\mu|$ in the six signal regions for the data and the expectation after the fit to data. Good agreement is observed between the corrected simulation samples and the data. The global goodness of fit when fitting the expectation from simulation, defined as twice the change in negative

log-likelihood relative to a fit performed assuming the pre-fit expectation per degree of freedom, has a value of 1.11 (P value of 0.29).

The separation between the μ_{prompt} and $\mu_{\tau(\to\mu)}$ processes can be seen clearly. The μ_{prompt} processes dominate at low $|d_0^\mu|$, whereas $\mu_{\tau(\to\mu)}$ dominates at high $|d_0^\mu|$. The μ_{had} background is also important at high $|d_0^\mu|$, but contributes most significantly at low p_{T}^μ.

The analysis was finalised before looking at the value of $R(\tau/\mu)$ in the data to minimize any bias. It was also checked that the result is consistent with respect to different channels, kinematic bins, data-taking periods and the charge of the probe lepton.

The total systematic uncertainty is 0.011, including the uncertainty in the $\tau \to \mu\nu_\mu\nu_\tau$ branching ratio, and the statistical uncertainty is 0.007. Table 1 lists the different contributions of systematic uncertainty grouped into categories. The leading contributions come from the imperfect knowledge of the tail of the $|d_0^\mu|$ distribution, the parton shower and hadronization model uncertainty, and the muon selection uncertainties.

The measured value of $R(\tau/\mu)$ is

$$R(\tau/\mu) = 0.992 \pm 0.013\,[\pm 0.007\,(\text{stat}) \pm 0.011\,(\text{syst})],$$

exceeding the precision from LEP which measured 1.070 ± 0.026. The result is shown in Fig. 4 alongside the combination of LEP measurements. The present result agrees with the SM expectation of equal couplings for different lepton flavours and the hypothesis of lepton-flavour universality.

This result surpasses the precision of the previous LEP result and resolves the tension they observed with the SM prediction of lepton-flavour universality. This precise measurement of $R(\tau/\mu)$ achieved so far, this is an example of the ability of the ATLAS experiment to perform high-precision measurements.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41567-021-01236-w.

Received: 28 July 2020; Accepted: 30 March 2021;
Published online: 5 July 2021

References

1. Feldman, G. J. et al. Measurement of the τ lifetime. *Phys. Rev. Lett.* **48**, 66–69 (1982).
2. Belle Collaboration Measurement of the τ-lepton lifetime at Belle. *Phys. Rev. Lett.* **112**, 031801 (2014).
3. LEP Electroweak Working Group Electroweak measurements in electron–positron collisions at W-boson-pair energies at LEP. *Phys. Rep.* **532**, 119–244 (2013).
4. Particle Data Group Review of particle physics. *Phys. Rev. D* **98**, 030001 (2018).
5. UA1 Collaboration Studies of intermediate vector boson production and decay in UA1 at the CERN proton–antiproton collider. *Z. Phys. C* **44**, 15–61 (1989).
6. CDF Collaboration Measurement of the ratio $B(W\to\tau\nu)/B(W\to e\nu)$ in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV. *Phys. Rev. Lett.* **68**, 3398–3402 (1992).
7. UA2 Collaboration A search for charged Higgs from top quark decay at the CERN $\bar{p}p$ collider. *Phys. Lett. B* **280**, 137–145 (1992).
8. D0 Collaboration Measurement of the $W\to\tau\nu$ production cross section in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV. *Phys. Rev. Lett.* **84**, 5710–5715 (2000).
9. CMS Collaboration Measurement of the top quark pair production cross section in dilepton final states containing one τ lepton in pp collisions at $\sqrt{s}=13$ TeV. *J. High Energy Phys.* **02**, 191 (2020).
10. LHCb Collaboration Measurement of forward $W\to e\nu$ production in pp collisions at $\sqrt{s}=8$ TeV. *J. High Energy Phys.* **10**, 030 (2016).
11. ATLAS Collaboration Precision measurement and interpretation of inclusive W^+, W^- and Z/γ^* production cross sections with the ATLAS detector. *Eur. Phys. J. C* **77**, 367 (2017).
12. Pich, A. Precision tau physics. *Prog. Part. Nucl. Phys.* **75**, 41–85 (2014).
13. LHCb Collaboration Measurement of the ratio of the $B^0\to D^{*-}\tau^+\nu_\tau$ and $B^0\to D^{*-}\mu^+\nu_\mu$ branching fractions using three-prong τ-lepton decays. *Phys. Rev. Lett.* **120**, 171802 (2018).
14. LHCb Collaboration Test of lepton flavor universality by the measurement of the $B^0\to D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong τ decays. *Phys. Rev. D* **97**, 072013 (2018).
15. LHCb Collaboration Measurement of CP-averaged observables in the $B^0\to K^{*0}\mu^+\mu^-$ decay. *Phys. Rev. Lett.* **125**, 011802 (2020).
16. LHCb Collaboration Angular analysis of the $B^0\to K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity. *J. High Energy Phys.* **02**, 104 (2016).
17. Belle Collaboration Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\overline{B}\to D^*\tau^-\overline{\nu}_\tau$. *Phys. Rev. Lett.* **118**, 211801 (2017).
18. Belle Collaboration Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\overline{B}\to D^*\tau^-\overline{\nu}_\tau$ with one-prong hadronic τ decays at Belle. *Phys. Rev. D* **97**, 012004 (2018).
19. Belle Collaboration Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method. Preprint at https://arxiv.org/pdf/1904.08794.pdf (2019).
20. BaBar Collaboration Evidence for an excess of $\overline{B}\to D^{(*)}\tau^-\overline{\nu}_\tau$ decays. *Phys. Rev. Lett.* **109**, 101802 (2012).
21. BaBar Collaboration Measurement of an excess of $\overline{B}\to D^{(*)}\tau^-\overline{\nu}_\tau$ decays and implications for charged Higgs bosons. *Phys. Rev. D* **88**, 072012 (2013).
22. ALEPH Collaboration Branching ratios and spectral functions of τ decays: final ALEPH measurements and physics implications. *Phys. Rep.* **421**, 191–284 (2005).
23. OPAL Collaboration A measurement of the $\tau\to\mu\overline{\nu}_\mu\nu_\tau$ branching ratio. *Phys. Lett. B* **551**, 35–48 (2003).
24. L3 Collaboration Measurement of the τ branching fractions into leptons. *Phys. Lett. B* **507**, 47–60 (2001).
25. DELPHI Collaboration Measurements of the leptonic branching fractions of the tau. *Eur. Phys. J. C* **10**, 201–218 (1999).
26. ATLAS Collaboration The ATLAS experiment at the CERN Large Hadron Collider. *J. Instrum.* **3**, S08003 (2008).
27. ATLAS Collaboration *ATLAS Insertable B- Layer Technical Design Report* CERN-LHCC-2010-013, ATLAS-TDR-19 (CERN, 2010); https://cds.cern.ch/record/1291633
28. Abbott, B. et al. Production and integration of the ATLAS insertable B-layer. *J. Instrum.* **13**, T05008 (2018).
29. ATLAS Collaboration Performance of the ATLAS trigger system in 2015. *Eur. Phys. J. C* **77**, 317 (2017).
30. ATLAS Collaboration Performance of electron and photon triggers in ATLAS during LHC run 2. *Eur. Phys. J. C* **80**, 47 (2020).
31. ATLAS Collaboration Performance of the ATLAS muon triggers in run 2. *J. Instrum.* **15**, P09015 (2020).
32. ATLAS Collaboration ATLAS data quality operations and performance for 2015–2018 data-taking. *J. Instrum.* **15**, P04003 (2020).
33. ATLAS Collaboration *Luminosity Determination in pp Collisions at* $\sqrt{s}=13$ TeV *using the ATLAS Detector at the LHC* (CERN, 2019); https://cds.cern.ch/record/2677054
34. Avoni, G. et al. The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS. *J. Instrum.* **13**, P07017 (2018).
35. Agostinelli, S. et al. GEANT4—a simulation toolkit. *Nucl. Instrum. Methods A* **506**, 250–303 (2003).
36. Voigt, W. Über das Gesetz der Intensitätsverteilung Innerhalb der Linien eines Gasspektrums. *Sitzungsberichte* **1914**, 25 (1912).
37. Cowan, G. et al. Asymptotic formulae for likelihood-based tests of new physics. *Eur. Phys. J. C* **71**, 1554 (2011); erratum **73**, 2501 (2013).
38. ATLAS Collaboration Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s}=13$ TeV. *Eur. Phys. J. C* **76**, 292 (2016).
39. ATLAS Collaboration *The Pythia 8 A3 Tune Description of ATLAS Minimum Bias and Inelastic Measurements Incorporating the Donnachie–Landshoff Diffractive Model* (CERN, 2016); https://cds.cern.ch/record/2206965

Methods

ATLAS coordinate system and nomenclature. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z axis along the beam pipe. The x axis points from the IP to the centre of the LHC ring, and the y axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

The beamline is the central (x–y) axis of the luminous region. The transverse impact parameter, $|d_0^\mu|$, is measured in the x–y plane as the closest distance of approach of the track to the beamline. It is defined relative to the beamline rather than the primary vertex so that the resolution of $|d_0^\mu|$ is independent of the vertex (x–y) resolution, which depends on the physics process.

Monte Carlo simulation and theoretical predictions. The top-pair and single-top-quark events, including Wt-, t- and s-channel production, were generated using the POWHEGBOX[40–44] generator interfaced to the PYTHIA8[45–47] parton shower and hadronization model (more details are available in ref. [48]). The decays of bottom and charm hadrons are important for backgrounds in the analysis and were modelled using the EvtGen[49] program. The $t\bar{t}$ and single-top processes were normalized to the inclusive cross-section calculation of the highest available precision[50–58] and $t\bar{t}$ events additionally have a differential reweighting applied to match the next-to-next-to-leading order (NNLO) in quantum chromodynamics (QCD) top quark p_{T} calculation[59]. For single-top quark production in the Wt channel, the diagram removal scheme[60] was used to remove overlap with $t\bar{t}$ production. The $t\bar{t}+W$ and $t\bar{t}+Z$ events were simulated with Sherpa and MadGraph5_aMC@NLO[61] interfaced with Pythia8, respectively. The background from $V(=W, Z)$+jets and VV+jets events was simulated with the Sherpa[44,62–71] generator (more details can be found in refs. [72,73]). All processes were normalized to their highest-order available cross-sections[74,75].

Simulated inelastic pp collisions[39] were overlaid on events in all samples to model the observed data distribution of pile-up from addition collisions in the same and neighbouring bunch crossings.

Object identification in ATLAS. Muons are reconstructed using combined fits of inner detector[76,77] and muon spectrometer tracks[38]. They are required to satisfy the 'medium' identification critera of ref. [38]. They are also required to be strictly isolated from other activity by requiring that the sum of the p_{T} of other tracks within a surrounding cone of size $\Delta R = 0.3$ and the sum of p_{T} calculated from calorimeter energy deposits within a cone of size $\Delta R = 0.2$ around the muons are below certain thresholds. Tag muons are required to have $p_{\mathrm{T}}^{\mu} > 27.3$ GeV to pass the trigger thresholds, while probe muons are required to have $p_{\mathrm{T}}^{\mu} > 5$ GeV. Both the tag and probe muons are required to have $|\eta| < 2.5$ and to originate close to the primary vertex with a distance of closest approach in the r–z plane of less than 0.3 mm and a transverse impact parameter relative to the beamline, $|d_0^\mu|$, of less than 0.5 mm. The primary vertex is defined as the vertex with the highest Σp_{T}^2 of the tracks associated with it. Additional criteria are applied to test the compatibility of the momenta measured separately in the inner detector and the muon spectrometer, to remove reconstructed muons that result from in-flight decays of charged kaons and pions.

Electrons are reconstructed from inner detector tracks matched to clusters of calorimeter-cell energy clusters[78]. They are required to satisfy the 'tight' identification criteria of ref. [78] and the same strict isolation criteria as applied to muons. Tag electrons are required to have $p_{\mathrm{T}}^{e} > 27$ GeV to pass the trigger requirements and satisfy $|\eta| < 2.47$, excluding the transition region between the barrel and end-cap calorimeter, $1.37 < |\eta| < 1.52$. They must also satisfy the same criteria as for muons for their distance of closest approach to the primary vertex in the transverse and r–z plane.

Hadronic jets are built from the energy in calorimeter cells at the electromagnetic energy scale[79], using the anti-k_t algorithm[80] with a radius parameter of 0.4. They are then calibrated to the energy scale of jets created from stable generator-level particles excluding muons and neutrinos, using the same jet algorithm[81]. For jets with $25 < p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$, pile-up suppression requirements in the form of a jet vertex tagger[82] are applied. Only jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ are considered in the analysis. To classify jets as containing a b hadron, the 70% efficiency working point of the MV2c10 b-tagging algorithm[83,84] is used.

An overlap removal procedure as described in ref. [85] is applied to resolve the ambiguity if lepton signals in the calorimeter are also reconstructed as hadronic jets.

Systematic uncertainties. Several of the most important systematic uncertainties in the measurement of $R(\tau/\mu)$ merit a more detailed discussion, which is provided here.

Owing to differences in the hadronic environment around the lepton between the Z and $t\bar{t}$ final states and the coarse binning in p_{T}^{μ} and $|\eta|$, which may not be able to encapsulate the full shape information, small biases can exist in the data-driven μ_{prompt} template distributions. The size of such a possible bias is estimated from the full difference between μ_{prompt} $|d_0^\mu|$ templates from Z and $t\bar{t}$ in simulation. This uncertainty is split into two components corresponding to the tail, $|d_0^\mu| \gtrsim 0.05$ mm, and core, $d_0^\mu| \lesssim 0.05$ mm, to prevent the data from constraining the uncertainty by using the full $|d_0^\mu|$ distribution.

The breakdown of uncertainties contributing to the μ_{had} background control region normalization in the e–μ (μ–μ) channels is as follows: 4% (4%) due to the size of the same-sign dataset; 8% (3%) due to the choice of Monte Carlo generators used; 1.0% (1.3%) due the uncertainty in the subtraction of the other processes in the same-sign control region.

The uncertainties due to the choice of Monte Carlo event generator for the μ_{prompt}, $\mu_{\tau(\to\mu)}$ and μ_{had} processes are estimated by varying different components of the modelling in a factorized way. The following variations are considered targeting different sources of uncertainty:

- Inital- and final-state radiation: A14 eigen-tune variations[46] of the strong coupling (α_{s})
- Missing higher-order QCD corrections: factorization and renormalization scales simultaneously varied up and down by a factor of two
- Resummation scale uncertainty: POWHEG h_{damp} parameter varied from 1.5 to 3 m_{top} (symmetrized)
- Parton shower and hadronization model: Herwig 7[86,87], H7UE tune[87,88] (symmetrized)
- Higher-order correction to top p_{T} spectrum: not applying the NNLO top p_{T} reweighting[59] (symmetrized)

In the cases where only a single alternative is given, the uncertainty is taken to be the deviation from the nominal result and then symmetrized, as indicated above. The effects on μ_{prompt} and $\mu_{\tau(\to\mu)}$ (collectively referred to as 'signal') are treated as correlated and the effects on μ_{had} are treated separately. The parton shower and hadronization uncertainty is separated into four nuisance parameters: one each corresponding to low and middle probe muon p_{T}^{μ} bins used in the fit, and two corresponding to the high p_{T}^{μ} bin where the uncertainty is further separated into components related to normalization and shape differences.

Auxiliary material. Additional auxiliary figures can be found at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/TOPQ-2018-29/.

Data availability

The experimental data that support the findings of this study are available in HEPData with the identifier https://www.hepdata.net/record/100232.

Code availability

The ATLAS software is available at the following link: https://gitlab.cern.ch/atlas/athena.

References

40. Frixione, S., Nason, P. & Ridolfi, G. A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction. *J. High Energy Phys.* **09**, 126 (2007).
41. Nason, P. A New method for combining NLO QCD with shower Monte Carlo algorithms. *J. High Energy Phys.* **11**, 040 (2004).
42. Frixione, S., Nason, P. & Oleari, C. Matching NLO QCD computations with parton shower simulations: the POWHEG method. *J. High Energy Phys.* **11**, 070 (2007).
43. Alioli, S. et al. A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. *J. High Energy Phys.* **06**, 043 (2010).
44. Ball, R. D. et al. Parton distributions for the LHC run II. *J. High Energy Phys.* **04**, 040 (2015).
45. Sjöstrand, T. et al. An introduction to PYTHIA 8.2. *Comput. Phys. Commun.* **191**, 159–177 (2015).
46. ATLAS Collaboration *ATLAS Pythia 8 Tunes to 7-TeV Data* (CERN, 2014); https://cds.cern.ch/record/1966419
47. Ball, R. D. et al. Parton distributions with LHC data. *Nucl. Phys. B* **867**, 244–289 (2013).
48. ATLAS Collaboration *Studies on Top-Quark Monte Carlo Modelling for Top2016* (CERN, 2016); https://cds.cern.ch/record/2216168
49. Lange, D. J. The 49 particle decay simulation package. *Nucl. Instrum. Methods A* **462**, 152–155 (2001).
50. Beneke, M. et al. Hadronic top-quark pair production with NNLL threshold resummation. *Nucl. Phys. B* **855**, 695–741 (2012).
51. Cacciari, M. et al. Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation. *Phys. Lett. B* **710**, 612–622 (2012).
52. Bärnreuther, P., Czakon, M. & Mitov, A. Percent-level-precision physics at the tevatron: next-to-next-to-leading order QCD corrections to $q\bar{q} \to t\bar{t}+X$. *Phys. Rev. Lett.* **109**, 132001 (2012).
53. Czakon, M. & Mitov, A. NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels. *J. High Energy Phys.* **12**, 054 (2012).

54. Czakon, M. & Mitov, A. NNLO corrections to top pair production at hadron colliders: the quark–gluon reaction. *J. High Energy Phys.* **01**, 080 (2013).
55. Czakon, M., Fiedler, P. & Mitov, A. Total top-quark pair-production cross section at hadron colliders through $\mathcal{O}(\alpha_S^4)$. *Phys. Rev. Lett.* **110**, 252004 (2013).
56. Czakon, M. & Mitov, A. Top++: a program for the calculation of the top-pair cross-section at hadron colliders. *Comput. Phys. Commun.* **185**, 2930–2938 (2014).
57. Aliev, M. et al. HATHOR: hadronic top and heavy quarks cross section calculator. *Comput. Phys. Commun.* **182**, 1034–1046 (2011).
58. Kant, P. et al. HATHOR for single top-quark production: updated predictions and uncertainty estimates for single top-quark production in hadronic collisions. *Comput. Phys. Commun.* **191**, 74–89 (2015).
59. Czakon, M. et al. Top-pair production at the LHC through NNLO QCD and NLO EW. *J. High Energy Phys.* **10**, 186 (2017).
60. Frixione, S. et al. Single-top hadroproduction in association with a W boson. *J. High Energy Phys.* **07**, 029 (2008).
61. Alwall, J. et al. The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *J. High Energy Phys.* **07**, 079 (2014).
62. Gleisberg, T. et al. Event generation with SHERPA 1.1. *J. High Energy Phys.* **02**, 007 (2009).
63. Bothmann, E. et al. Event generation with Sherpa 2.2. *SciPost Phys.* **7**, 034 (2019).
64. Gleisberg, T. & Höche, S. Comix, a new matrix element generator. *J. High Energy Phys.* **12**, 039 (2008).
65. Cascioli, F., Maierhofer, P. & Pozzorini, S. Scattering amplitudes with open loops. *Phys. Rev. Lett.* **108**, 111601 (2012).
66. Denner, A., Dittmaier, S. & Hofer, L. Collier: a fortran-based complex one-loop library in extended regularizations. *Comput. Phys. Commun.* **212**, 220–238 (2017).
67. Schumann, S. & Krauss, F. A parton shower algorithm based on Catani–Seymour dipole factorisation. *J. High Energy Phys.* **03**, 038 (2008).
68. Höche, S. et al. A critical appraisal of NLO+PS matching methods. *J. High Energy Phys.* **09**, 049 (2012).
69. Höche, S. et al. QCD matrix elements+parton showers: the NLO case. *J. High Energy Phys.* **04**, 027 (2013).
70. Catani, S. et al. QCD matrix elements+parton showers. *J. High Energy Phys.* **11**, 063 (2001).
71. Höche, S. et al. QCD matrix elements and truncated showers. *J. High Energy Phys.* **05**, 053 (2009).
72. ATLAS Collaboration *ATLAS Simulation of Boson Plus Jets Processes in Run 2* (CERN, 2017); https://cds.cern.ch/record/2261937
73. ATLAS Collaboration *Multi-Boson Simulation for 13-TeV ATLAS Analyses* (CERN, 2017); https://cds.cern.ch/record/2261933
74. Anastasiou, C. et al. High precision QCD at hadron colliders: electroweak gauge boson rapidity distributions at NNLO. *Phys. Rev. D* **69**, 094008 (2004).
75. de Florian, D. et al. *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector* CERN-2017-002-M. Preprint at https://arxiv.org/pdf/1610.07922.pdf (2016).
76. ATLAS Collaboration Performance of the ATLAS track reconstruction algorithms in dense environments in LHC run 2. *Eur. Phys. J. C* **77**, 673 (2017).
77. ATLAS Collaboration *Early Inner Detector Tracking Performance in the 2015 Data at* $\sqrt{s} = 13$ TeV (CERN, 2015); https://cds.cern.ch/record/2110140
78. ATLAS Collaboration Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data. *J. Instrum.* **14**, P12006 (2019).
79. ATLAS Collaboration Topological cell clustering in the ATLAS calorimeters and its performance in LHC run 1. *Eur. Phys. J. C* **77**, 490 (2017).
80. Cacciari, M., Salam, G. P. & Soyez, G. The anti-k_t jet clustering algorithm. *J. High Energy Phys.* **04**, 063 (2008).
81. ATLAS Collaboration Jet energy scale measurements and their systematic uncertainties in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Phys. Rev. D* **96**, 072002 (2017).
82. ATLAS Collaboration Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector. *Eur. Phys. J. C* **76**, 581 (2016).
83. ATLAS Collaboration Measurements of b-jet tagging efficiency with the ATLAS detector using $t\bar{t}$ events at $t\bar{t}$. *J. High Energy Phys.* **08**, 089 (2018).
84. ATLAS Collaboration ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $t\bar{t}$. *Eur. Phys. J. C* **79**, 970 (2019).
85. Aad, G. et al. Observation of the associated production of a top quark and a Z boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *J. High Energy Phys.* **07**, 124 (2020).
86. Bähr, M. et al. Herwig++ physics and manual. *Eur. Phys. J. C* **58**, 639–707 (2008).
87. Bellm, J. et al. Herwig 7.0/Herwig++ 3.0 release note. *Eur. Phys. J. C* **76**, 196 (2016).
88. Harland-Lang, L. et al. Parton distributions in the LHC era: MMHT 2014 PDFs. *Eur. Phys. J. C* **75**, 204 (2015).

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions, without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRT, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russia Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; ERC, ERDF, Horizon 2020, Marie Skłodowska-Curie Actions and COST, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom) and BNL (United States), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed at https://cds.cern.ch/record/2717821.

Author contributions

All authors have contributed to the publication, being variously involved in the design and the construction of the detectors, in writing software, calibrating subsystems, operating the detectors and acquiring data, and finally analysing the processed data. The ATLAS Collaboration members discussed and approved the scientific results. The manuscript was prepared by a subgroup of authors appointed by the collaboration and subject to an internal collaboration-wide review process. All authors reviewed and approved the final version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to G.A.

Peer review information *Nature Physics* thanks Thomas Kuhr and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

ATLAS Collaboration

G. Aad[1]✉, B. Abbott[2], D. C. Abbott[3], A. Abed Abud[4], K. Abeling[5], D. K. Abhayasinghe[6], S. H. Abidi[7], O. S. AbouZeid[8], N. L. Abraham[9], H. Abramowicz[10], H. Abreu[11], Y. Abulaiti[12], B. S. Acharya[13,14], B. Achkar[5], L. Adam[15], C. Adam Bourdarios[16], L. Adamczyk[17], L. Adamek[7], J. Adelman[18], M. Adersberger[19], A. Adiguzel[20], S. Adorni[21], T. Adye[22], A. A. Affolder[23], Y. Afik[11], C. Agapopoulou[24], M. N. Agaras[25], A. Aggarwal[26], C. Agheorghiesei[27], J. A. Aguilar-Saavedra[28,29], A. Ahmad[4], F. Ahmadov[30], W. S. Ahmed[31], X. Ai[32], G. Aielli[33,34], S. Akatsuka[35], M. Akbiyik[15], T. P. A. Åkesson[36], E. Akilli[21], A. V. Akimov[37], K. Al Khoury[24], G. L. Alberghi[38,39], J. Albert[40], M. J. Alconada Verzini[10], S. Alderweireldt[4], M. Aleksa[4], I. N. Aleksandrov[30], C. Alexa[41], T. Alexopoulos[42], A. Alfonsi[43], F. Alfonsi[38,39], M. Alhroob[2], B. Ali[44], S. Ali[45], M. Aliev[46], G. Alimonti[47], C. Allaire[4], B. M. M. Allbrooke[9], B. W. Allen[48], P. P. Allport[49], A. Aloisio[50,51], F. Alonso[52], C. Alpigiani[53], E. Alunno Camelia[33,34], M. Alvarez Estevez[54], M. G. Alviggi[50,51], Y. Amaral Coutinho[55], A. Ambler[31], L. Ambroz[56], C. Amelung[57], D. Amidei[58], S. P. Amor Dos Santos[28], S. Amoroso[59], C. S. Amrouche[21], F. An[60], C. Anastopoulos[61], N. Andari[62], T. Andeen[63], J. K. Anders[64], S. Y. Andrean[65,66], A. Andreazza[47,67], V. Andrei[68], C. R. Anelli[40], S. Angelidakis[69], A. Angerami[70], A. V. Anisenkov[71,72], A. Annovi[73], C. Antel[21], M. T. Anthony[61], E. Antipov[74], M. Antonelli[75], D. J. A. Antrim[76], F. Anulli[77], M. Aoki[78], J. A. Aparisi Pozo[79], M. A. Aparo[9], L. Aperio Bella[59], N. Aranzabal[4], V. Araujo Ferraz[80], R. Araujo Pereira[55], C. Arcangeletti[75], A. T. H. Arce[81], F. A. Arduh[52], J.-F. Arguin[82], S. Argyropoulos[83], J.-H. Arling[59], A. J. Armbruster[4], A. Armstrong[76], O. Arnaez[7], H. Arnold[43], Z. P. Arrubarrena Tame[19], G. Artoni[56], H. Asada[84], K. Asai[85], S. Asai[86], T. Asawatavonvanich[87], N. Asbah[88], E. M. Asimakopoulou[89], L. Asquith[9], J. Assahsah[90], K. Assamagan[91], R. Astalos[92], R. J. Atkin[93], M. Atkinson[94], N. B. Atlay[95], H. Atmani[24], K. Augsten[44], V. A. Austrup[96], G. Avolio[4], M. K. Ayoub[97], G. Azuelos[82], H. Bachacou[62], K. Bachas[98], F. Backman[65,66], P. Bagnaia[77,99], M. Bahmani[100], H. Bahrasemani[101], A. J. Bailey[79], V. R. Bailey[94], J. T. Baines[22], C. Bakalis[42], O. K. Baker[102], P. J. Bakker[43], E. Bakos[103], D. Bakshi Gupta[104], S. Balaji[105], R. Balasubramanian[43], E. M. Baldin[72,71], P. Balek[106], F. Balli[62], W. K. Balunas[56], J. Balz[15], E. Banas[100], M. Bandieramonte[107], A. Bandyopadhyay[108], Sw. Banerjee[109], L. Barak[10], W. M. Barbe[25], E. L. Barberio[110], D. Barberis[111,112], M. Barbero[1], G. Barbour[113], T. Barillari[114], M.-S. Barisits[4], J. Barkeloo[48], T. Barklow[115], R. Barnea[11], B. M. Barnett[22], R. M. Barnett[32], Z. Barnovska-Blenessy[116], A. Baroncelli[116], G. Barone[91], A. J. Barr[56], L. Barranco Navarro[65,66], F. Barreiro[54], J. Barreiro Guimarães da Costa[97], U. Barron[10], S. Barsov[117], F. Bartels[68], R. Bartoldus[115], G. Bartolini[1], A. E. Barton[118], P. Bartos[92], A. Basalaev[59], A. Basan[15], A. Bassalat[24], M. J. Basso[7], R. L. Bates[119], S. Batlamous[120], J. R. Batley[121], B. Batool[122], M. Battaglia[23], M. Bauce[77,99], F. Bauer[62,273], P. Bauer[108], H. S. Bawa[123], A. Bayirli[20], J. B. Beacham[81], T. Beau[124], P. H. Beauchemin[125], F. Becherer[83], P. Bechtle[108], H. C. Beck[5], H. P. Beck[64,239], K. Becker[126], C. Becot[59], A. Beddall[127], A. J. Beddall[128], V. A. Bednyakov[30], M. Bedognetti[43], C. P. Bee[129], T. A. Beermann[96], M. Begalli[55], M. Begel[91], A. Behera[129], J. K. Behr[59], F. Beisiegel[108], M. Belfkir[16], A. S. Bell[113], G. Bella[10], L. Bellagamba[39], A. Bellerive[130], P. Bellos[69], K. Beloborodov[72,71], K. Belotskiy[131], N. L. Belyaev[131], D. Benchekroun[132], N. Benekos[42], Y. Benhammou[10], D. P. Benjamin[12], M. Benoit[91], J. R. Bensinger[57], S. Bentvelsen[43], L. Beresford[56], M. Beretta[75], D. Berge[95], E. Bergeaas Kuutmann[89], N. Berger[16], B. Bergmann[44], L. J. Bergsten[57], J. Beringer[32], S. Berlendis[133], G. Bernardi[124], C. Bernius[115], F. U. Bernlochner[108], T. Berry[6], P. Berta[15], A. Berthold[134], I. A. Bertram[118], O. Bessidskaia Bylund[96], N. Besson[62], A. Bethani[135], S. Bethke[114], A. Betti[136], A. J. Bevan[137], J. Beyer[114], D. S. Bhattacharya[138], P. Bhattarai[57], V. S. Bhopatkar[12], R. Bi[107], R. M. Bianchi[107], O. Biebel[19], D. Biedermann[95], R. Bielski[4],

K. Bierwagen[15], N. V. Biesuz[73,139], M. Biglietti[140], T. R. V. Billoud[44], M. Bindi[5], A. Bingul[127], C. Bini[77,99], S. Biondi[39,38], C. J. Birch-sykes[135], M. Birman[106], T. Bisanz[4], J. P. Biswal[141], D. Biswas[109], A. Bitadze[135], C. Bittrich[134], K. Bjørke[142], T. Blazek[92], I. Bloch[59], C. Blocker[57], A. Blue[119], U. Blumenschein[137], G. J. Bobbink[43], V. S. Bobrovnikov[72,71], S. S. Bocchetta[36], D. Bogavac[143], A. G. Bogdanchikov[72,71], C. Bohm[65], V. Boisvert[6], P. Bokan[89,5], T. Bold[17], A. E. Bolz[144], M. Bomben[124], M. Bona[137], J. S. Bonilla[48], M. Boonekamp[62], C. D. Booth[6], A. G. Borbély[119], H. M. Borecka-Bielska[145], L. S. Borgna[113], A. Borisov[146], G. Borissov[118], D. Bortoletto[56], D. Boscherini[39], M. Bosman[143], J. D. Bossio Sola[31], K. Bouaouda[132], J. Boudreau[107], E. V. Bouhova-Thacker[118], D. Boumediene[25], A. Boveia[147], J. Boyd[4], D. Boye[148], I. R. Boyko[30], A. J. Bozson[6], J. Bracinik[49], N. Brahimi[149,150], G. Brandt[96], O. Brandt[121], F. Braren[59], B. Brau[3], J. E. Brau[48], W. D. Breaden Madden[119], K. Brendlinger[59], R. Brener[11], L. Brenner[4], R. Brenner[89], S. Bressler[106], B. Brickwedde[15], D. L. Briglin[49], D. Britton[119], D. Britzger[114], I. Brock[108], R. Brock[151], G. Brooijmans[70], W. K. Brooks[152], E. Brost[91], P. A. Bruckman de Renstrom[100], B. Brüers[59], D. Bruncko[153], A. Bruni[39], G. Bruni[39], M. Bruschi[39], N. Bruscino[77,99], L. Bryngemark[115], T. Buanes[154], Q. Buat[129], P. Buchholz[122], A. G. Buckley[119], I. A. Budagov[30], M. K. Bugge[142], F. Bührer[83], O. Bulekov[131], B. A. Bullard[88], T. J. Burch[18], S. Burdin[145], C. D. Burgard[43], A. M. Burger[74], B. Burghgrave[104], J. T. P. Burr[59], C. D. Burton[63], J. C. Burzynski[3], V. Büscher[15], E. Buschmann[5], P. J. Bussey[119], J. M. Butler[155], C. M. Buttar[119], J. M. Butterworth[113], P. Butti[4], W. Buttinger[4], C. J. Buxo Vazquez[151], A. Buzatu[45], A. R. Buzykaev[72,71], G. Cabras[39,38], S. Cabrera Urbán[79], D. Caforio[156], H. Cai[107], V. M. M. Cairo[115], O. Cakir[157], N. Calace[4], P. Calafiura[32], G. Calderini[124], P. Calfayan[158], G. Callea[119], L. P. Caloba[55], A. Caltabiano[33,34], S. Calvente Lopez[54], D. Calvet[25], S. Calvet[25], T. P. Calvet[1], M. Calvetti[73,139], R. Camacho Toro[124], S. Camarda[4], D. Camarero Munoz[54], P. Camarri[33,34], M. T. Camerlingo[140,159], D. Cameron[142], C. Camincher[4], S. Campana[4], M. Campanelli[113], A. Camplani[8], V. Canale[50,51], A. Canesse[31], M. Cano Bret[160], J. Cantero[74], T. Cao[10], Y. Cao[94], M. D. M. Capeans Garrido[4], M. Capua[161,162], R. Cardarelli[33], F. Cardillo[79], G. Carducci[161,162], I. Carli[163], T. Carli[4], G. Carlino[50], B. T. Carlson[107], E. M. Carlson[40,164], L. Carminati[47,67], R. M. D. Carney[115], S. Caron[26], E. Carquin[152], S. Carrá[59], G. Carratta[39,38], J. W. S. Carter[7], T. M. Carter[165], M. P. Casado[143,240], A. F. Casha[7], E. G. Castiglia[102], F. L. Castillo[79], L. Castillo Garcia[143], V. Castillo Gimenez[79], N. F. Castro[28,166], A. Catinaccio[4], J. R. Catmore[142], A. Cattai[4], V. Cavaliere[91], V. Cavasinni[73,139], E. Celebi[167], F. Celli[56], K. Cerny[168], A. S. Cerqueira[80], A. Cerri[9], L. Cerrito[33,34], F. Cerutti[32], A. Cervelli[39,38], S. A. Cetin[167], Z. Chadi[132], D. Chakraborty[18], J. Chan[109], W. S. Chan[43], W. Y. Chan[145], J. D. Chapman[121], B. Chargeishvili[169], D. G. Charlton[49], T. P. Charman[137], M. Chatterjee[64], C. C. Chau[130], S. Che[147], S. Chekanov[12], S. V. Chekulaev[164], G. A. Chelkov[30,241], B. Chen[60], C. Chen[116], C. H. Chen[60], H. Chen[170], H. Chen[91], J. Chen[116], J. Chen[70], J. Chen[57], S. Chen[171], S. J. Chen[170], X. Chen[172], Y. Chen[116], Y.-H. Chen[59], H. C. Cheng[173], H. J. Cheng[97], A. Cheplakov[30], E. Cheremushkina[146], R. Cherkaoui El Moursli[120], E. Cheu[133], K. Cheung[174], T. J. A. Chevalérias[62], L. Chevalier[62], V. Chiarella[75], G. Chiarelli[73], G. Chiodini[175], A. S. Chisholm[49], A. Chitan[41], I. Chiu[86], Y. H. Chiu[40], M. V. Chizhov[30], K. Choi[63], A. R. Chomont[77,99], Y. S. Chow[43], L. D. Christopher[176], M. C. Chu[173], X. Chu[97,177], J. Chudoba[178], J. J. Chwastowski[100], L. Chytka[168], D. Cieri[114], K. M. Ciesla[100], V. Cindro[179], I. A. Cioară[41], A. Ciocio[32], F. Cirotto[50,51], Z. H. Citron[106,242], M. Citterio[47], D. A. Ciubotaru[41], B. M. Ciungu[7], A. Clark[21], M. R. Clark[70], P. J. Clark[165], S. E. Clawson[135], C. Clement[65,66], Y. Coadou[1], M. Cobal[13,180], A. Coccaro[112], J. Cochran[60], R. Coelho Lopes De Sa[3], H. Cohen[10], A. E. C. Coimbra[4], B. Cole[70], A. P. Colijn[43], J. Collot[181], P. Conde Muiño[28,182], S. H. Connell[148], I. A. Connelly[119], S. Constantinescu[41], F. Conventi[50,243], A. M. Cooper-Sarkar[56], F. Cormier[183], K. J. R. Cormier[7], L. D. Corpe[113], M. Corradi[77,99], E. E. Corrigan[36],

F. Corriveau[31,244], M. J. Costa[79], F. Costanza[16], D. Costanzo[61], G. Cowan[6], J. W. Cowley[121], J. Crane[135], K. Cranmer[184], R. A. Creager[171], S. Crépé-Renaudin[181], F. Crescioli[124], M. Cristinziani[108], V. Croft[125], G. Crosetti[162,161], A. Cueto[16], T. Cuhadar Donszelmann[76], H. Cui[97,177], A. R. Cukierman[115], W. R. Cunningham[119], S. Czekierda[100], P. Czodrowski[4], M. M. Czurylo[144], M. J. Da Cunha Sargedas De Sousa[185], J. V. Da Fonseca Pinto[55], C. Da Via[135], W. Dabrowski[17], F. Dachs[4], T. Dado[186], S. Dahbi[176], T. Dai[58], C. Dallapiccola[3], M. Dam[8], G. D'amen[91], V. D'Amico[140,159], J. Damp[15], J. R. Dandoy[171], M. F. Daneri[187], M. Danninger[101], V. Dao[4], G. Darbo[112], O. Dartsi[16], A. Dattagupta[48], T. Daubney[59], S. D'Auria[47,67], C. David[188], T. Davidek[163], D. R. Davis[81], I. Dawson[61], K. De[104], R. De Asmundis[50], M. De Beurs[43], S. De Castro[39,38], N. De Groot[26], P. de Jong[43], H. De la Torre[151], A. De Maria[170], D. De Pedis[77], A. De Salvo[77], U. De Sanctis[33,34], M. De Santis[33,34], A. De Santo[9], J. B. De Vivie De Regie[24], D. V. Dedovich[30], A. M. Deiana[136], J. Del Peso[54], Y. Delabat Diaz[59], D. Delgove[24], F. Deliot[62], C. M. Delitzsch[133], M. Della Pietra[50,51], D. Della Volpe[21], A. Dell'Acqua[4], L. Dell'Asta[33,34], M. Delmastro[16], C. Delporte[24], P. A. Delsart[181], D. A. DeMarco[7], S. Demers[102], M. Demichev[30], G. Demontigny[82], S. P. Denisov[146], L. D'Eramo[18], D. Derendarz[100], J. E. Derkaoui[90], F. Derue[124], P. Dervan[145], K. Desch[108], K. Dette[7], C. Deutsch[108], M. R. Devesa[187], P. O. Deviveiros[4], F. A. Di Bello[77,99], A. Di Ciaccio[33,34], L. Di Ciaccio[16], W. K. Di Clemente[171], C. Di Donato[50,51], A. Di Girolamo[4], G. Di Gregorio[73,139], B. Di Micco[140,159], R. Di Nardo[140,159], K. F. Di Petrillo[88], R. Di Sipio[7], C. Diaconu[1], F. A. Dias[43], T. Dias Do Vale[28], M. A. Diaz[189], F. G. Diaz Capriles[108], J. Dickinson[32], M. Didenko[46], E. B. Diehl[58], J. Dietrich[95], S. Díez Cornell[59], C. Diez Pardos[122], A. Dimitrievska[32], W. Ding[172], J. Dingfelder[108], S. J. Dittmeier[144], F. Dittus[4], F. Djama[1], T. Djobava[169], J. I. Djuvsland[154], M. A. B. Do Vale[190], M. Dobre[41], D. Dodsworth[57], C. Doglioni[36], J. Dolejsi[163], Z. Dolezal[163], M. Donadelli[191], B. Dong[149], J. Donini[25], A. D'onofrio[170], M. D'Onofrio[145], J. Dopke[22], A. Doria[50], M. T. Dova[52], A. T. Doyle[119], E. Drechsler[101], E. Dreyer[101], T. Dreyer[5], A. S. Drobac[125], D. Du[185], T. A. du Pree[43], Y. Duan[150], F. Dubinin[37], M. Dubovsky[92], A. Dubreuil[21], E. Duchovni[106], G. Duckeck[19], O. A. Ducu[4,41], D. Duda[114], A. Dudarev[4], A. C. Dudder[15], E. M. Duffield[32], M. D'uffizi[135], L. Duflot[24], M. Dührssen[4], C. Dülsen[96], M. Dumancic[106], A. E. Dumitriu[41], M. Dunford[68], A. Duperrin[1], H. Duran Yildiz[157], M. Düren[156], A. Durglishvili[169], D. Duschinger[134], B. Dutta[59], D. Duvnjak[192], G. I. Dyckes[171], M. Dyndal[4], S. Dysch[135], B. S. Dziedzic[100], M. G. Eggleston[81], T. Eifert[104], G. Eigen[154], K. Einsweiler[32], T. Ekelof[89], H. El Jarrari[120], V. Ellajosyula[89], M. Ellert[89], F. Ellinghaus[96], A. A. Elliot[137], N. Ellis[4], J. Elmsheuser[91], M. Elsing[4], D. Emeliyanov[22], A. Emerman[70], Y. Enari[86], M. B. Epland[81], J. Erdmann[186], A. Ereditato[64], P. A. Erland[100], M. Errenst[96], M. Escalier[24], C. Escobar[79], O. Estrada Pastor[79], E. Etzion[10], G. Evans[28,193], H. Evans[158], M. O. Evans[9], A. Ezhilov[117], F. Fabbri[119], L. Fabbri[39,38], V. Fabiani[26], G. Facini[126], R. M. Fakhrutdinov[146], S. Falciano[77], P. J. Falke[108], S. Falke[4], J. Faltova[163], Y. Fang[97], Y. Fang[97], G. Fanourakis[194], M. Fanti[47,67], M. Faraj[13,180], A. Farbin[104], A. Farilla[140], E. M. Farina[195,196], T. Farooque[151], S. M. Farrington[165], P. Farthouat[4], F. Fassi[120], P. Fassnacht[4], D. Fassouliotis[69], M. Faucci Giannelli[165], W. J. Fawcett[121], L. Fayard[24], O. L. Fedin[117,245], W. Fedorko[183], A. Fehr[64], M. Feickert[94], L. Feligioni[1], A. Fell[61], C. Feng[185], M. Feng[81], M. J. Fenton[76], A. B. Fenyuk[146], S. W. Ferguson[197], J. Ferrando[59], A. Ferrante[94], A. Ferrari[89], P. Ferrari[43], R. Ferrari[195], D. E. Ferreira de Lima[144], A. Ferrer[79], D. Ferrere[21], C. Ferretti[58], F. Fiedler[15], A. Filipčič[179], F. Filthaut[26], K. D. Finelli[155], M. C. N. Fiolhais[28,198,246], L. Fiorini[79], F. Fischer[19], J. Fischer[15], W. C. Fisher[151], T. Fitschen[49], I. Fleck[122], P. Fleischmann[58], T. Flick[96], B. M. Flierl[19], L. Flores[171], L. R. Flores Castillo[173], F. M. Follega[199,200], N. Fomin[154], J. H. Foo[7], G. T. Forcolin[199,200], B. C. Forland[158], A. Formica[62], F. A. Förster[143], A. C. Forti[135], E. Fortin[1], M. G. Foti[56], D. Fournier[24], H. Fox[118], P. Francavilla[73,139],

S. Francescato[77,99], M. Franchini[39,38], S. Franchino[68], D. Francis[4], L. Franco[16], L. Franconi[64], M. Franklin[88], G. Frattari[77,99], A. N. Fray[137], P. M. Freeman[49], B. Freund[82], W. S. Freund[55], E. M. Freundlich[186], D. C. Frizzell[2], D. Froidevaux[4], J. A. Frost[56], M. Fujimoto[85], C. Fukunaga[201], E. Fullana Torregrosa[79], T. Fusayasu[202], J. Fuster[79], A. Gabrielli[39,38], A. Gabrielli[4], S. Gadatsch[21], P. Gadow[114], G. Gagliardi[112,111], L. G. Gagnon[82], G. E. Gallardo[56], E. J. Gallas[56], B. J. Gallop[22], R. Gamboa Goni[137], K. K. Gan[147], S. Ganguly[106], J. Gao[116], Y. Gao[165], Y. S. Gao[123,247], F. M. Garay Walls[189], C. García[79], J. E. García Navarro[79], J. A. García Pascual[97], C. Garcia-Argos[83], M. Garcia-Sciveres[32], R. W. Gardner[203], N. Garelli[115], S. Gargiulo[83], C. A. Garner[7], V. Garonne[142], S. J. Gasiorowski[53], P. Gaspar[55], A. Gaudiello[112,111], G. Gaudio[195], P. Gauzzi[77,99], I. L. Gavrilenko[37], A. Gavrilyuk[204], C. Gay[183], G. Gaycken[59], E. N. Gazis[42], A. A. Geanta[41], C. M. Gee[23], C. N. P. Gee[22], J. Geisen[36], M. Geisen[15], C. Gemme[112], M. H. Genest[181], C. Geng[58], S. Gentile[77,99], S. George[6], T. Geralis[194], L. O. Gerlach[5], P. Gessinger-Befurt[15], G. Gessner[186], S. Ghasemi[122], M. Ghasemi Bostanabad[40], M. Ghneimat[122], A. Ghosh[24], A. Ghosh[160], B. Giacobbe[39], S. Giagu[77,99], N. Giangiacomi[39,38], P. Giannetti[73], A. Giannini[50,51], G. Giannini[143], S. M. Gibson[6], M. Gignac[23], D. T. Gil[205], B. J. Gilbert[70], D. Gillberg[130], G. Gilles[96], N. E. K. Gillwald[59], D. M. Gingrich[141], M. P. Giordani[13,180], P. F. Giraud[62], G. Giugliarelli[13,180], D. Giugni[47], F. Giuli[33,34], S. Gkaitatzis[98], I. Gkialas[69,248], E. L. Gkougkousis[143], P. Gkountoumis[42], L. K. Gladilin[206], C. Glasman[54], J. Glatzer[143], P. C. F. Glaysher[59], A. Glazov[59], G. R. Gledhill[48], I. Gnesi[162,249], M. Goblirsch-Kolb[57], D. Godin[82], S. Goldfarb[110], T. Golling[21], D. Golubkov[146], A. Gomes[28,193], R. Goncalves Gama[5], R. Gonçalo[28,198], G. Gonella[48], L. Gonella[49], A. Gongadze[30], F. Gonnella[49], J. L. Gonski[70], S. González de la Hoz[79], S. Gonzalez Fernandez[143], R. Gonzalez Lopez[145], C. Gonzalez Renteria[32], R. Gonzalez Suarez[89], S. Gonzalez-Sevilla[21], G. R. Gonzalvo Rodriguez[79], L. Goossens[4], N. A. Gorasia[49], P. A. Gorbounov[204], H. A. Gordon[91], B. Gorini[4], E. Gorini[175,207], A. Gorišek[179], A. T. Goshaw[81], M. I. Gostkin[30], C. A. Gottardo[26], M. Gouighri[208], A. G. Goussiou[53], N. Govender[148], C. Goy[16], I. Grabowska-Bold[17], E. C. Graham[145], J. Gramling[76], E. Gramstad[142], S. Grancagnolo[95], M. Grandi[9], V. Gratchev[117], P. M. Gravila[209], F. G. Gravili[175,207], C. Gray[119], H. M. Gray[32], C. Grefe[108], K. Gregersen[36], I. M. Gregor[59], P. Grenier[115], K. Grevtsov[59], C. Grieco[143], N. A. Grieser[2], A. A. Grillo[23], K. Grimm[123,250], S. Grinstein[143,251], J.-F. Grivaz[24], S. Groh[15], E. Gross[106], J. Grosse-Knetter[5], Z. J. Grout[113], C. Grud[58], A. Grummer[210], J. C. Grundy[56], L. Guan[58], W. Guan[109], C. Gubbels[183], J. Guenther[211], A. Guerguichon[24], J. G. R. Guerrero Rojas[79], F. Guescini[114], D. Guest[76], R. Gugel[15], A. Guida[59], T. Guillemin[16], S. Guindon[4], J. Guo[149], W. Guo[58], Y. Guo[116], Z. Guo[1], R. Gupta[59], S. Gurbuz[20], G. Gustavino[2], M. Guth[83], P. Gutierrez[2], C. Gutschow[113], C. Guyot[62], C. Gwenlan[56], C. B. Gwilliam[145], E. S. Haaland[142], A. Haas[184], C. Haber[32], H. K. Hadavand[104], A. Hadef[116], M. Haleem[138], J. Haley[74], J. J. Hall[61], G. Halladjian[151], G. D. Hallewell[1], K. Hamano[40], H. Hamdaoui[120], M. Hamer[108], G. N. Hamity[165], K. Han[116,24], L. Han[170], L. Han[116], S. Han[32], Y. F. Han[7], K. Hanagaki[78,252], M. Hance[23], D. M. Handl[19], M. D. Hank[203], R. Hankache[124], E. Hansen[36], J. B. Hansen[8], J. D. Hansen[8], M. C. Hansen[108], P. H. Hansen[8], E. C. Hanson[135], K. Hara[212], T. Harenberg[96], S. Harkusha[213], P. F. Harrison[126], N. M. Hartman[115], N. M. Hartmann[19], Y. Hasegawa[214], A. Hasib[165], S. Hassani[62], S. Haug[64], R. Hauser[151], L. B. Havener[70], M. Havranek[44], C. M. Hawkes[49], R. J. Hawkings[4], S. Hayashida[84], D. Hayden[151], C. Hayes[58], R. L. Hayes[183], C. P. Hays[56], J. M. Hays[137], H. S. Hayward[145], S. J. Haywood[22], F. He[116], Y. He[87], M. P. Heath[165], V. Hedberg[36], A. L. Heggelund[142], C. Heidegger[83], K. K. Heidegger[83], W. D. Heidorn[60], J. Heilman[130], S. Heim[59], T. Heim[32], B. Heinemann[59,253], J. G. Heinlein[171], J. J. Heinrich[48], L. Heinrich[4], J. Hejbal[178], L. Helary[59], A. Held[184], S. Hellesund[142], C. M. Helling[23], S. Hellman[65,66], C. Helsens[4], R. C. W. Henderson[118], Y. Heng[109], L. Henkelmann[121], A. M. Henriques Correia[4], H. Herde[57], Y. Hernández Jiménez[176], H. Herr[15], M. G. Herrmann[19],

T. Herrmann[134], G. Herten[83], R. Hertenberger[19], L. Hervas[4], T. C. Herwig[171], G. G. Hesketh[113], N. P. Hessey[164], H. Hibi[215], S. Higashino[78], E. Higón-Rodriguez[79], K. Hildebrand[203], J. C. Hill[121], K. K. Hill[91], K. H. Hiller[59], S. J. Hillier[49], M. Hils[134], I. Hinchliffe[32], F. Hinterkeuser[108], M. Hirose[216], S. Hirose[212], D. Hirschbuehl[96], B. Hiti[179], O. Hladik[178], J. Hobbs[129], N. Hod[106], M. C. Hodgkinson[61], A. Hoecker[4], D. Hohn[83], D. Hohov[24], T. Holm[108], T. R. Holmes[203], M. Holzbock[114], L. B. A. H. Hommels[121], T. M. Hong[107], J. C. Honig[83], A. Hönle[114], B. H. Hooberman[94], W. H. Hopkins[12], Y. Horii[84], P. Horn[134], L. A. Horyn[203], S. Hou[45], A. Hoummada[132], J. Howarth[119], J. Hoya[52], M. Hrabovsky[168], J. Hrivnac[24], A. Hrynevich[217], T. Hryn'ova[16], P. J. Hsu[174], S.-C. Hsu[53], Q. Hu[91], S. Hu[149], Y. F. Hu[97,177,254], D. P. Huang[113], X. Huang[170], Y. Huang[116], Y. Huang[97], Z. Hubacek[44], F. Hubaut[1], M. Huebner[108], F. Huegging[108], T. B. Huffman[56], M. Huhtinen[4], R. Hulsken[181], R. F. H. Hunter[130], N. Huseynov[30,255], J. Huston[151], J. Huth[88], R. Hyneman[115], S. Hyrych[92], G. Iacobucci[21], G. Iakovidis[91], I. Ibragimov[122], L. Iconomidou-Fayard[24], P. Iengo[4], R. Ignazzi[8], O. Igonkina[43,256,273], R. Iguchi[86], T. Iizawa[21], Y. Ikegami[78], M. Ikeno[78], N. Ilic[26,7,244], F. Iltzsche[134], H. Imam[132], G. Introzzi[195,196], M. Iodice[140], K. Iordanidou[164], V. Ippolito[77,99], M. F. Isacson[89], M. Ishino[86], W. Islam[74], C. Issever[95,59], S. Istin[11], J. M. Iturbe Ponce[173], R. Iuppa[199,200], A. Ivina[106], J. M. Izen[197], V. Izzo[50], P. Jacka[178], P. Jackson[192], R. M. Jacobs[59], B. P. Jaeger[101], V. Jain[218], G. Jäkel[96], K. B. Jakobi[15], K. Jakobs[83], T. Jakoubek[106], J. Jamieson[119], K. W. Janas[17], R. Jansky[21], M. Janus[5], P. A. Janus[17], G. Jarlskog[36], A. E. Jaspan[145], N. Javadov[30,255], T. Javůrek[4], M. Javurkova[3], F. Jeanneau[62], L. Jeanty[48], J. Jejelava[219], P. Jenni[83,257], N. Jeong[59], S. Jézéquel[16], H. Ji[109], J. Jia[129], Z. Jia[170], H. Jiang[60], Y. Jiang[116], Z. Jiang[115], S. Jiggins[83], F. A. Jimenez Morales[25], J. Jimenez Pena[114], S. Jin[170], A. Jinaru[41], O. Jinnouchi[87], H. Jivan[176], P. Johansson[61], K. A. Johns[133], C. A. Johnson[158], E. Jones[126], R. W. L. Jones[118], S. D. Jones[9], T. J. Jones[145], J. Jongmanns[68], J. Jovicevic[4], X. Ju[32], J. J. Junggeburth[114], A. Juste Rozas[143,251], A. Kaczmarska[100], M. Kado[77,99], H. Kagan[147], M. Kagan[115], A. Kahn[70], C. Kahra[15], T. Kaji[220], E. Kajomovitz[11], C. W. Kalderon[91], A. Kaluza[15], A. Kamenshchikov[146], M. Kaneda[86], N. J. Kang[23], S. Kang[60], Y. Kano[84], J. Kanzaki[78], L. S. Kaplan[109], D. Kar[176], K. Karava[56], M. J. Kareem[188], I. Karkanias[98], S. N. Karpov[30], Z. M. Karpova[30], V. Kartvelishvili[118], A. N. Karyukhin[146], E. Kasimi[98], A. Kastanas[65,66], C. Kato[150], J. Katzy[59], K. Kawade[214], K. Kawagoe[221], T. Kawaguchi[84], T. Kawamoto[62], G. Kawamura[5], E. F. Kay[40], S. Kazakos[143], V. F. Kazanin[72,71], J. M. Keaveney[93], R. Keeler[40], J. S. Keller[130], E. Kellermann[36], D. Kelsey[9], J. J. Kempster[49], J. Kendrick[49], K. E. Kennedy[70], O. Kepka[178], S. Kersten[96], B. P. Kerševan[179], S. Ketabchi Haghighat[7], M. Khader[94], F. Khalil-Zada[222], M. Khandoga[62], A. Khanov[74], A. G. Kharlamov[72,71], T. Kharlamova[72,71], E. E. Khoda[183], A. Khodinov[46], T. J. Khoo[211], G. Khoriauli[138], E. Khramov[30], J. Khubua[169], S. Kido[215], M. Kiehn[4], E. Kim[87], Y. K. Kim[203], N. Kimura[113], A. Kirchhoff[5], D. Kirchmeier[134], J. Kirk[22], A. E. Kiryunin[114], T. Kishimoto[86], D. P. Kisliuk[7], V. Kitali[59], C. Kitsaki[42], O. Kivernyk[108], T. Klapdor-Kleingrothaus[83], M. Klassen[68], C. Klein[130], M. H. Klein[58], M. Klein[145], U. Klein[145], K. Kleinknecht[15], P. Klimek[4], A. Klimentov[91], T. Klingl[108], T. Klioutchnikova[4], F. F. Klitzner[19], P. Kluit[43], S. Kluth[114], E. Kneringer[211], E. B. F. G. Knoops[1], A. Knue[83], D. Kobayashi[221], M. Kobel[134], M. Kocian[115], T. Kodama[86], P. Kodys[163], D. M. Koeck[9], P. T. Koenig[108], T. Koffas[130], N. M. Köhler[4], M. Kolb[62], I. Koletsou[16], T. Komarek[168], T. Kondo[78], K. Köneke[83], A. X. Y. Kong[192], A. C. König[26], T. Kono[85], V. Konstantinides[113], N. Konstantinidis[113], B. Konya[36], R. Kopeliansky[158], S. Koperny[17], K. Korcyl[100], K. Kordas[98], G. Koren[10], A. Korn[113], I. Korolkov[143], E. V. Korolkova[61], N. Korotkova[206], O. Kortner[114], S. Kortner[114], V. V. Kostyukhin[61,46], A. Kotsokechagia[24], A. Kotwal[81], A. Koulouris[42], A. Kourkoumeli-Charalampidi[195,196], C. Kourkoumelis[69], E. Kourlitis[12], V. Kouskoura[91], R. Kowalewski[40], W. Kozanecki[135], A. S. Kozhin[146], V. A. Kramarenko[206], G. Kramberger[179], D. Krasnopevtsev[116], M. W. Krasny[124], A. Krasznahorkay[4], D. Krauss[114], J. A. Kremer[15], J. Kretzschmar[145], P. Krieger[7],

F. Krieter[19], A. Krishnan[144], M. Krivos[163], K. Krizka[32], K. Kroeninger[186], H. Kroha[114], J. Kroll[178], J. Kroll[171], K. S. Krowpman[151], U. Kruchonak[30], H. Krüger[108], N. Krumnack[60], M. C. Kruse[81], J. A. Krzysiak[100], A. Kubota[87], O. Kuchinskaia[46], S. Kuday[223], D. Kuechler[59], J. T. Kuechler[59], S. Kuehn[4], T. Kuhl[59], V. Kukhtin[30], Y. Kulchitsky[213,258], S. Kuleshov[224], Y. P. Kulinich[94], M. Kuna[181], A. Kupco[178], T. Kupfer[186], O. Kuprash[83], H. Kurashige[215], L. L. Kurchaninov[164], Y. A. Kurochkin[213], A. Kurova[131], M. G. Kurth[97,177], E. S. Kuwertz[4], M. Kuze[87], A. K. Kvam[53], J. Kvita[168], T. Kwan[31], F. La Ruffa[162,161], C. Lacasta[79], F. Lacava[77,99], D. P. J. Lack[135], H. Lacker[95], D. Lacour[124], E. Ladygin[30], R. Lafaye[16], B. Laforge[124], T. Lagouri[225], S. Lai[5], I. K. Lakomiec[17], J. E. Lambert[2], S. Lammers[158], W. Lampl[133], C. Lampoudis[98], E. Lançon[91], U. Landgraf[83], M. P. J. Landon[137], V. S. Lang[83], J. C. Lange[5], R. J. Langenberg[3], A. J. Lankford[76], F. Lanni[91], K. Lantzsch[108], A. Lanza[195], A. Lapertosa[112,111], J. F. Laporte[62], T. Lari[47], F. Lasagni Manghi[39,38], M. Lassnig[4], V. Latonova[178], T. S. Lau[173], A. Laudrain[15], A. Laurier[130], M. Lavorgna[50,51], S. D. Lawlor[6], M. Lazzaroni[47,67], B. Le[135], E. Le Guirriec[1], A. Lebedev[60], M. LeBlanc[133], T. LeCompte[12], F. Ledroit-Guillon[181], A. C. A. Lee[113], C. A. Lee[91], G. R. Lee[154], L. Lee[88], S. C. Lee[45], S. Lee[60], B. Lefebvre[164], H. P. Lefebvre[6], M. Lefebvre[40], C. Leggett[32], K. Lehmann[101], N. Lehmann[64], G. Lehmann Miotto[4], W. A. Leight[59], A. Leisos[98,259], M. A. L. Leite[191], C. E. Leitgeb[19], R. Leitner[163], D. Lellouch[106,273], K. J. C. Leney[136], T. Lenz[108], S. Leone[73], C. Leonidopoulos[165], A. Leopold[124], C. Leroy[82], R. Les[151], C. G. Lester[121], M. Levchenko[117], J. Levêque[16], D. Levin[58], L. J. Levinson[106], D. J. Lewis[49], B. Li[172], B. Li[58], C.-Q. Li[149,150], F. Li[149], H. Li[116], H. Li[185], J. Li[149], K. Li[53], L. Li[149], M. Li[97,177], Q. Li[97,177], Q. Y. Li[116], S. Li[150,149], X. Li[59], Y. Li[59], Z. Li[185], Z. Li[56], Z. Li[31], Z. Liang[97], M. Liberatore[59], B. Liberti[33], K. Lie[226], S. Lim[91], C. Y. Lin[121], K. Lin[151], R. A. Linck[158], R. E. Lindley[133], J. H. Lindon[49], A. Linss[59], A. L. Lionti[21], E. Lipeles[171], A. Lipniacka[154], T. M. Liss[94,260], A. Lister[183], J. D. Little[104], B. Liu[60], B. X. Liu[101], H. B. Liu[91], J. B. Liu[116], J. K. K. Liu[203], K. Liu[150,149], M. Liu[116], M. Y. Liu[116], P. Liu[97], X. Liu[116], Y. Liu[59], Y. Liu[97,177], Y. L. Liu[58], Y. W. Liu[116], M. Livan[195,196], A. Lleres[181], J. Llorente Merino[101], S. L. Lloyd[137], C. Y. Lo[227], E. M. Lobodzinska[59], P. Loch[133], S. Loffredo[33,34], T. Lohse[95], K. Lohwasser[61], M. Lokajicek[178], J. D. Long[94], R. E. Long[118], I. Longarini[77,99], L. Longo[4], K. A. Looper[147], I. Lopez Paz[135], A. Lopez Solis[61], J. Lorenz[19], N. Lorenzo Martinez[16], A. M. Lory[19], P. J. Lösel[19], A. Lösle[83], X. Lou[65,66], X. Lou[97], A. Lounis[24], J. Love[12], P. A. Love[118], J. J. Lozano Bahilo[79], M. Lu[116], Y. J. Lu[174], H. J. Lubatti[53], C. Luci[77,99], F. L. Lucio Alves[170], A. Lucotte[181], F. Luehring[158], I. Luise[129], L. Luminari[77], B. Lund-Jensen[228], M. S. Lutz[10], D. Lynn[91], H. Lyons[145], R. Lysak[178], E. Lytken[36], F. Lyu[97], V. Lyubushkin[30], T. Lyubushkina[30], H. Ma[91], L. L. Ma[185], Y. Ma[113], D. M. Mac Donell[40], G. Maccarrone[75], A. Macchiolo[114], C. M. Macdonald[61], J. C. MacDonald[61], J. Machado Miguens[171], D. Madaffari[79], R. Madar[25], W. F. Mader[134], M. Madugoda Ralalage Don[74], N. Madysa[134], J. Maeda[215], T. Maeno[91], M. Maerker[134], V. Magerl[83], N. Magini[60], J. Magro[13,180,261], D. J. Mahon[70], C. Maidantchik[55], T. Maier[19], A. Maio[28,193,229], K. Maj[17], O. Majersky[92], S. Majewski[48], Y. Makida[78], N. Makovec[24], B. Malaescu[124], Pa. Malecki[100], V. P. Maleev[117], F. Malek[181], D. Malito[162,161], U. Mallik[160], C. Malone[121], S. Maltezos[42], S. Malyukov[30], J. Mamuzic[79], G. Mancini[75], I. Mandić[179], L. Manhaes de Andrade Filho[80], I. M. Maniatis[98], J. Manjarres Ramos[134], K. H. Mankinen[36], A. Mann[19], A. Manousos[211], B. Mansoulie[62], I. Manthos[98], S. Manzoni[43], A. Marantis[98], G. Marceca[187], L. Marchese[56], G. Marchiori[124], M. Marcisovsky[178], L. Marcoccia[33,34], C. Marcon[36], M. Marjanovic[2], Z. Marshall[32], M. U. F. Martensson[89], S. Marti-Garcia[79], C. B. Martin[147], T. A. Martin[126], V. J. Martin[165], B. Martin dit Latour[154], L. Martinelli[140,159], M. Martinez[143,251], P. Martinez Agullo[79], V. I. Martinez Outschoorn[3], S. Martin-Haugh[22], V. S. Martoiu[41], A. C. Martyniuk[113], A. Marzin[4], S. R. Maschek[114], L. Masetti[15], T. Mashimo[86], R. Mashinistov[37], J. Masik[135], A. L. Maslennikov[72,71], L. Massa[39,38], P. Massarotti[50,51], P. Mastrandrea[73,139], A. Mastroberardino[162,161], T. Masubuchi[86], D. Matakias[91], A. Matic[19], N. Matsuzawa[86], P. Mättig[108],

J. Maurer[41], B. Maček[179], D. A. Maximov[72,71], R. Mazini[45], I. Maznas[98], S. M. Mazza[23], J. P. Mc Gowan[31], S. P. Mc Kee[58], T. G. McCarthy[114], W. P. McCormack[32], E. F. McDonald[110], A. E. McDougall[43], J. A. Mcfayden[32], G. Mchedlidze[169], M. A. McKay[136], K. D. McLean[40], S. J. McMahon[22], P. C. McNamara[110], C. J. McNicol[126], R. A. McPherson[40,244], J. E. Mdhluli[176], Z. A. Meadows[3], S. Meehan[4], T. Megy[25], S. Mehlhase[19], A. Mehta[145], B. Meirose[197], D. Melini[11], B. R. Mellado Garcia[176], J. D. Mellenthin[5], M. Melo[92], F. Meloni[59], A. Melzer[108], E. D. Mendes Gouveia[28,166], A. M. Mendes Jacques Da Costa[49], L. Meng[4], X. T. Meng[58], S. Menke[114], E. Meoni[162,161], S. Mergelmeyer[95], S. A. M. Merkt[107], C. Merlassino[56], P. Mermod[21], L. Merola[50,51], C. Meroni[47], G. Merz[58], O. Meshkov[206,37], J. K. R. Meshreki[122], J. Metcalfe[12], A. S. Mete[12], C. Meyer[158], J.-P. Meyer[62], M. Michetti[95], R. P. Middleton[22], L. Mijović[165], G. Mikenberg[106], M. Mikestikova[178], M. Mikuž[179], H. Mildner[61], A. Milic[7], C. D. Milke[136], D. W. Miller[203], L. S. Miller[130], A. Milov[106], D. A. Milstead[65,66], R. A. Mina[115], A. A. Minaenko[146], I. A. Minashvili[169], A. I. Mincer[184], B. Mindur[17], M. Mineev[30], Y. Minegishi[86], Y. Mino[35], L. M. Mir[143], M. Mironova[56], K. P. Mistry[171], T. Mitani[220], J. Mitrevski[19], V. A. Mitsou[79], M. Mittal[149], O. Miu[7], A. Miucci[64], P. S. Miyagawa[137], A. Mizukami[78], J. U. Mjörnmark[36], T. Mkrtchyan[68], M. Mlynarikova[18], T. Moa[65,66], S. Mobius[5], K. Mochizuki[82], P. Mogg[19], S. Mohapatra[70], R. Moles-Valls[108], K. Mönig[59], E. Monnier[1], A. Montalbano[101], J. Montejo Berlingen[4], M. Montella[113], F. Monticelli[52], S. Monzani[47], N. Morange[24], A. L. Moreira De Carvalho[28], D. Moreno[230], M. Moreno Llácer[79], C. Moreno Martinez[143], P. Morettini[112], M. Morgenstern[11], S. Morgenstern[134], D. Mori[101], M. Morii[88], M. Morinaga[220], V. Morisbak[142], A. K. Morley[4], G. Mornacchi[4], A. P. Morris[113], L. Morvaj[129], P. Moschovakos[4], B. Moser[43], M. Mosidze[169], T. Moskalets[62], P. Moskvitina[26], J. Moss[123,262], E. J. W. Moyse[3], S. Muanza[1], J. Mueller[107], R. S. P. Mueller[19], D. Muenstermann[118], G. A. Mullier[36], D. P. Mungo[47,67], J. L. Munoz Martinez[143], F. J. Munoz Sanchez[135], P. Murin[153], W. J. Murray[126,22], A. Murrone[47,67], J. M. Muse[2], M. Muškinja[32], C. Mwewa[93], A. G. Myagkov[146,241], A. A. Myers[107], G. Myers[158], J. Myers[48], M. Myska[44], B. P. Nachman[32], O. Nackenhorst[186], A. Nag Nag[134], K. Nagai[56], K. Nagano[78], Y. Nagasaka[231], J. L. Nagle[91], E. Nagy[1], A. M. Nairz[4], Y. Nakahama[84], K. Nakamura[78], T. Nakamura[86], H. Nanjo[216], F. Napolitano[68], R. F. Naranjo Garcia[59], R. Narayan[136], I. Naryshkin[117], M. Naseri[130], T. Naumann[59], G. Navarro[230], P. Y. Nechaeva[37], F. Nechansky[59], T. J. Neep[49], A. Negri[195,196], M. Negrini[39], C. Nellist[26], C. Nelson[31], M. E. Nelson[65,66], S. Nemecek[178], M. Nessi[4,263], M. S. Neubauer[94], F. Neuhaus[15], M. Neumann[96], R. Newhouse[183], P. R. Newman[49], C. W. Ng[107], Y. S. Ng[95], Y. W. Y. Ng[76], B. Ngair[120], H. D. N. Nguyen[1], T. Nguyen Manh[82], E. Nibigira[25], R. B. Nickerson[56], R. Nicolaidou[62], D. S. Nielsen[8], J. Nielsen[23], M. Niemeyer[5], N. Nikiforou[63], V. Nikolaenko[146,241], I. Nikolic-Audit[124], K. Nikolopoulos[49], P. Nilsson[91], H. R. Nindhito[21], A. Nisati[77], N. Nishu[149], R. Nisius[114], I. Nitsche[186], T. Nitta[220], T. Nobe[86], D. L. Noel[121], Y. Noguchi[35], I. Nomidis[124], M. A. Nomura[91], M. Nordberg[4], J. Novak[179], T. Novak[179], O. Novgorodova[134], R. Novotny[44], L. Nozka[168], K. Ntekas[76], E. Nurse[113], F. G. Oakham[130], H. Oberlack[114], J. Ocariz[124], A. Ochi[215], I. Ochoa[70], J. P. Ochoa-Ricoux[189], K. O'Connor[57], S. Oda[221], S. Odaka[78], S. Oerdek[5], A. Ogrodnik[17], A. Oh[135], C. C. Ohm[228], H. Oide[87], M. L. Ojeda[7], H. Okawa[212], Y. Okazaki[35], M. W. O'Keefe[145], Y. Okumura[86], A. Olariu[41], L. F. Oleiro Seabra[28], S. A. Olivares Pino[189], D. Oliveira Damazio[91], J. L. Oliver[192], M. J. R. Olsson[76], A. Olszewski[100], J. Olszowska[100], Ö. O. Öncel[108], D. C. O'Neil[101], A. P. O'neill[56], A. Onofre[28,166], P. U. E. Onyisi[63], H. Oppen[142], R. G. Oreamuno Madriz[18], M. J. Oreglia[203], G. E. Orellana[52], D. Orestano[140,159], N. Orlando[143], R. S. Orr[7], V. O'Shea[119], R. Ospanov[116], G. Otero y Garzon[187], H. Otono[221], P. S. Ott[68], G. J. Ottino[32], M. Ouchrif[90], J. Ouellette[91], F. Ould-Saada[142], A. Ouraou[62,273], Q. Ouyang[97], M. Owen[119], R. E. Owen[22], V. E. Ozcan[20], N. Ozturk[104],

J. Pacalt[168], H. A. Pacey[121], K. Pachal[81], A. Pacheco Pages[143], C. Padilla Aranda[143], S. Pagan Griso[32], G. Palacino[158], S. Palazzo[165], S. Palestini[4], M. Palka[205], P. Palni[17], C. E. Pandini[21], J. G. Panduro Vazquez[6], P. Pani[59], G. Panizzo[13,180], L. Paolozzi[21], C. Papadatos[82], K. Papageorgiou[69,248], S. Parajuli[136], A. Paramonov[12], C. Paraskevopoulos[42], D. Paredes Hernandez[227], S. R. Paredes Saenz[56], B. Parida[106], T. H. Park[7], A. J. Parker[123], M. A. Parker[121], F. Parodi[112,111], E. W. Parrish[18], J. A. Parsons[70], U. Parzefall[83], L. Pascual Dominguez[124], V. R. Pascuzzi[32], J. M. P. Pasner[23], F. Pasquali[43], E. Pasqualucci[77], S. Passaggio[112], F. Pastore[6], P. Pasuwan[65,66], S. Pataraia[15], J. R. Pater[135], A. Pathak[109], J. Patton[145], T. Pauly[4], J. Pearkes[115], B. Pearson[114], M. Pedersen[142], L. Pedraza Diaz[26], R. Pedro[28], T. Peiffer[5], S. V. Peleganchuk[72,71], O. Penc[178], C. Peng[227], H. Peng[116], B. S. Peralva[80], M. M. Perego[24], A. P. Pereira Peixoto[28], L. Pereira Sanchez[65,66], D. V. Perepelitsa[91], E. Perez Codina[164], F. Peri[95], L. Perini[47,67], H. Pernegger[4], S. Perrella[4], A. Perrevoort[43], K. Peters[59], R. F. Y. Peters[135], B. A. Petersen[4], T. C. Petersen[8], E. Petit[1], V. Petousis[44], C. Petridou[98], F. Petrucci[140,159], M. Pettee[102], N. E. Pettersson[3], K. Petukhova[163], A. Peyaud[62], R. Pezoa[152], L. Pezzotti[195,196], T. Pham[110], P. W. Phillips[22], M. W. Phipps[94], G. Piacquadio[129], E. Pianori[32], A. Picazio[3], R. H. Pickles[135], R. Piegaia[187], D. Pietreanu[41], J. E. Pilcher[203], A. D. Pilkington[135], M. Pinamonti[13,180], J. L. Pinfold[141], C. Pitman Donaldson[113], M. Pitt[10], L. Pizzimento[33,34], A. Pizzini[43], M.-A. Pleier[91], V. Plesanovs[83], V. Pleskot[163], E. Plotnikova[30], P. Podberezko[72,71], R. Poettgen[36], R. Poggi[21], L. Poggioli[124], I. Pogrebnyak[151], D. Pohl[108], I. Pokharel[5], G. Polesello[195], A. Poley[101,164], A. Policicchio[77,99], R. Polifka[163], A. Polini[39], C. S. Pollard[59], V. Polychronakos[91], D. Ponomarenko[131], L. Pontecorvo[4], S. Popa[232], G. A. Popeneciu[233], L. Portales[16], D. M. Portillo Quintero[181], S. Pospisil[44], K. Potamianos[59], I. N. Potrap[30], C. J. Potter[121], H. Potti[63], T. Poulsen[36], J. Poveda[79], T. D. Powell[61], G. Pownall[59], M. E. Pozo Astigarraga[4], A. Prades Ibanez[79], P. Pralavorio[1], M. M. Prapa[194], S. Prell[60], D. Price[135], M. Primavera[175], M. L. Proffitt[53], N. Proklova[131], K. Prokofiev[226], F. Prokoshin[30], S. Protopopescu[91], J. Proudfoot[12], M. Przybycien[17], D. Pudzha[117], A. Puri[94], P. Puzo[24], D. Pyatiizbyantseva[131], J. Qian[58], Y. Qin[135], A. Quadt[5], M. Queitsch-Maitland[4], M. Racko[92], F. Ragusa[47,67], G. Rahal[234], J. A. Raine[21], S. Rajagopalan[91], A. Ramirez Morales[137], K. Ran[97,177], D. M. Rauch[59], F. Rauscher[19], S. Rave[15], B. Ravina[119], I. Ravinovich[106], J. H. Rawling[135], M. Raymond[4], A. L. Read[142], N. P. Readioff[61], M. Reale[175,207], D. M. Rebuzzi[195,196], G. Redlinger[91], K. Reeves[197], D. Reikher[10], A. Reiss[15], A. Rej[122], C. Rembser[4], A. Renardi[59], M. Renda[41], M. B. Rendel[114], A. G. Rennie[119], S. Resconi[47], E. D. Resseguie[32], S. Rettie[113], B. Reynolds[147], E. Reynolds[49], O. L. Rezanova[72,71], P. Reznicek[163], E. Ricci[199,200], R. Richter[114], S. Richter[59], E. Richter-Was[205], M. Ridel[124], P. Rieck[114], O. Rifki[59], M. Rijssenbeek[129], A. Rimoldi[195,196], M. Rimoldi[59], L. Rinaldi[39], T. T. Rinn[94], G. Ripellino[228], I. Riu[143], P. Rivadeneira[59], J. C. Rivera Vergara[40], F. Rizatdinova[74], E. Rizvi[137], C. Rizzi[4], S. H. Robertson[31,244], M. Robin[59], D. Robinson[121], C. M. Robles Gajardo[152], M. Robles Manzano[15], A. Robson[119], A. Rocchi[33,34], E. Rocco[15], C. Roda[73,139], S. Rodriguez Bosca[79], A. Rodriguez Rodriguez[83], A. M. Rodríguez Vera[188], S. Roe[4], J. Roggel[96], O. Røhne[142], R. Röhrig[114], R. A. Rojas[152], B. Roland[83], C. P. A. Roland[158], J. Roloff[91], A. Romaniouk[131], M. Romano[39,38], N. Rompotis[145], M. Ronzani[184], L. Roos[124], S. Rosati[77], G. Rosin[3], B. J. Rosser[171], E. Rossi[59], E. Rossi[140,159], E. Rossi[50,51], L. P. Rossi[112], L. Rossini[59], R. Rosten[143], M. Rotaru[41], B. Rottler[83], D. Rousseau[24], G. Rovelli[195,196], A. Roy[63], D. Roy[176], A. Rozanov[1], Y. Rozen[11], X. Ruan[176], T. A. Ruggeri[192], F. Rühr[83], A. Ruiz-Martinez[79], A. Rummler[4], Z. Rurikova[83], N. A. Rusakovich[30], H. L. Russell[31], L. Rustige[25,186], J. P. Rutherfoord[133], E. M. Rüttinger[61], M. Rybar[163], G. Rybkin[24], E. B. Rye[142], A. Ryzhov[146], J. A. Sabater Iglesias[59], P. Sabatini[79], L. Sabetta[77,99], S. Sacerdoti[24], H. F.-W. Sadrozinski[23], R. Sadykov[30], F. Safai Tehrani[77], B. Safarzadeh Samani[9], M. Safdari[115], P. Saha[18], S. Saha[31], M. Sahinsoy[114], A. Sahu[96], M. Saimpert[4], M. Saito[86], T. Saito[86],

H. Sakamoto[86], D. Salamani[21], G. Salamanna[140,159], A. Salnikov[115], J. Salt[79], A. Salvador Salas[143], D. Salvatore[162,161], F. Salvatore[9], A. Salvucci[173], A. Salzburger[4], J. Samarati[4], D. Sammel[83], D. Sampsonidis[98], D. Sampsonidou[98], J. Sánchez[79], A. Sanchez Pineda[13,4,180], H. Sandaker[142], C. O. Sander[59], I. G. Sanderswood[118], M. Sandhoff[96], C. Sandoval[235], D. P. C. Sankey[22], M. Sannino[112,111], Y. Sano[84], A. Sansoni[75], C. Santoni[25], H. Santos[28,193], S. N. Santpur[32], A. Santra[79], K. A. Saoucha[61], A. Sapronov[30], J. G. Saraiva[28,229], O. Sasaki[78], K. Sato[212], F. Sauerburger[83], E. Sauvan[16], P. Savard[7], R. Sawada[86], C. Sawyer[22], L. Sawyer[236,264], I. Sayago Galvan[79], C. Sbarra[39], A. Sbrizzi[13,180], T. Scanlon[113], J. Schaarschmidt[53], P. Schacht[114], D. Schaefer[203], L. Schaefer[171], U. Schäfer[15], A. C. Schaffer[24], D. Schaile[19], R. D. Schamberger[129], E. Schanet[19], C. Scharf[95], N. Scharmberg[135], V. A. Schegelsky[117], D. Scheirich[163], F. Schenck[95], M. Schernau[76], C. Schiavi[112,111], L. K. Schildgen[108], Z. M. Schillaci[57], E. J. Schioppa[175,207], M. Schioppa[162,161], K. E. Schleicher[83], S. Schlenker[4], K. R. Schmidt-Sommerfeld[114], K. Schmieden[15], C. Schmitt[15], S. Schmitt[59], L. Schoeffel[62], A. Schoening[144], P. G. Scholer[83], E. Schopf[56], M. Schott[15], J. F. P. Schouwenberg[26], J. Schovancova[4], S. Schramm[21], F. Schroeder[96], A. Schulte[15], H.-C. Schultz-Coulon[68], M. Schumacher[83], B. A. Schumm[23], Ph. Schune[62], A. Schwartzman[115], T. A. Schwarz[58], Ph. Schwemling[62], R. Schwienhorst[151], A. Sciandra[23], G. Sciolla[57], M. Scornajenghi[162,161], F. Scuri[73], F. Scutti[110], L. M. Scyboz[114], C. D. Sebastiani[145], P. Seema[95], S. C. Seidel[210], A. Seiden[23], B. D. Seidlitz[91], T. Seiss[203], C. Seitz[59], J. M. Seixas[55], G. Sekhniaidze[50], S. J. Sekula[136], N. Semprini-Cesari[39,38], S. Sen[81], C. Serfon[91], L. Serin[24], L. Serkin[13,14], M. Sessa[116], H. Severini[2], S. Sevova[115], F. Sforza[112,111], A. Sfyrla[21], E. Shabalina[5], J. D. Shahinian[171], N. W. Shaikh[65,66], D. Shaked Renous[106], L. Y. Shan[97], M. Shapiro[32], A. Sharma[4], A. S. Sharma[192], P. B. Shatalov[204], K. Shaw[9], S. M. Shaw[135], M. Shehade[106], Y. Shen[2], A. D. Sherman[155], P. Sherwood[113], L. Shi[113], C. O. Shimmin[102], Y. Shimogama[220], M. Shimojima[202], J. D. Shinner[6], I. P. J. Shipsey[56], S. Shirabe[87], M. Shiyakova[30,265], J. Shlomi[106], A. Shmeleva[37], M. J. Shochet[203], J. Shojaii[110], D. R. Shope[228], S. Shrestha[147], E. M. Shrif[176], M. J. Shroff[40], E. Shulga[106], P. Sicho[178], A. M. Sickles[94], E. Sideras Haddad[176], O. Sidiropoulou[4], A. Sidoti[39,38], F. Siegert[134], Dj. Sijacki[103], M. Jr. Silva[109], M. V. Silva Oliveira[4], S. B. Silverstein[65], S. Simion[24], R. Simoniello[15], C. J. Simpson-allsop[49], S. Simsek[167], P. Sinervo[7], V. Sinetckii[206], S. Singh[101], M. Sioli[39,38], I. Siral[48], S. Yu. Sivoklokov[206], J. Sjölin[65,66], A. Skaf[5], E. Skorda[36], P. Skubic[2], M. Slawinska[100], K. Sliwa[125], R. Slovak[163], V. Smakhtin[106], B. H. Smart[22], J. Smiesko[153], N. Smirnov[131], S. Yu. Smirnov[131], Y. Smirnov[131], L. N. Smirnova[206,266], O. Smirnova[36], E. A. Smith[203], H. A. Smith[56], M. Smizanska[118], K. Smolek[44], A. Smykiewicz[100], A. A. Snesarev[37], H. L. Snoek[43], I. M. Snyder[48], S. Snyder[91], R. Sobie[40,244], A. Soffer[10], A. Søgaard[165], F. Sohns[5], C. A. Solans Sanchez[4], E. Yu. Soldatov[131], U. Soldevila[79], A. A. Solodkov[146], A. Soloshenko[30], O. V. Solovyanov[146], V. Solovyev[117], P. Sommer[61], H. Son[125], A. Sonay[143], W. Song[22], W. Y. Song[188], A. Sopczak[44], A. L. Sopio[113], F. Sopkova[153], S. Sottocornola[195,196], R. Soualah[13,180], A. M. Soukharev[72,71], D. South[59], S. Spagnolo[175,207], M. Spalla[114], M. Spangenberg[126], F. Spanò[6], D. Sperlich[83], T. M. Spieker[68], G. Spigo[4], M. Spina[9], D. P. Spiteri[119], M. Spousta[163], A. Stabile[47,67], B. L. Stamas[18], R. Stamen[68], M. Stamenkovic[43], A. Stampekis[49], E. Stanecka[100], B. Stanislaus[56], M. M. Stanitzki[59], M. Stankaityte[56], B. Stapf[43], E. A. Starchenko[146], G. H. Stark[23], J. Stark[181], P. Staroba[178], P. Starovoitov[68], S. Stärz[31], R. Staszewski[100], G. Stavropoulos[194], M. Stegler[59], P. Steinberg[91], A. L. Steinhebel[48], B. Stelzer[101,164], H. J. Stelzer[107], O. Stelzer-Chilton[164], H. Stenzel[156], T. J. Stevenson[9], G. A. Stewart[4], M. C. Stockton[4], G. Stoicea[41], M. Stolarski[28], S. Stonjek[114], A. Straessner[134], J. Strandberg[228], S. Strandberg[65,66], M. Strauss[2], T. Strebler[1], P. Strizenec[153], R. Ströhmer[138], D. M. Strom[48], R. Stroynowski[136], A. Strubig[65,66], S. A. Stucci[91], B. Stugu[154], J. Stupak[2], N. A. Styles[59], D. Su[115], W. Su[149,53], X. Su[116],

V. V. Sulin[37], M. J. Sullivan[145], D. M. S. Sultan[21], S. Sultansoy[237], T. Sumida[35], S. Sun[58], X. Sun[135], C. J. E. Suster[105], M. R. Sutton[9], S. Suzuki[78], M. Svatos[178], M. Swiatlowski[164], S. P. Swift[218], T. Swirski[138], A. Sydorenko[15], I. Sykora[92], M. Sykora[163], T. Sykora[163], D. Ta[15], K. Tackmann[59,267], J. Taenzer[10], A. Taffard[76], R. Tafirout[164], E. Tagiev[146], R. Takashima[238], K. Takeda[215], T. Takeshita[214], E. P. Takeva[165], Y. Takubo[78], M. Talby[1], A. A. Talyshev[72,71], K. C. Tam[227], N. M. Tamir[10], J. Tanaka[86], R. Tanaka[24], S. Tapia Araya[94], S. Tapprogge[15], A. Tarek Abouelfadl Mohamed[151], S. Tarem[11], K. Tariq[185], G. Tarna[41,268], G. F. Tartarelli[47], P. Tas[163], M. Tasevsky[178], E. Tassi[162,161], A. Tavares Delgado[28], Y. Tayalati[120], A. J. Taylor[165], G. N. Taylor[110], W. Taylor[188], H. Teagle[145], A. S. Tee[118], R. Teixeira De Lima[115], P. Teixeira-Dias[6], H. Ten Kate[4], J. J. Teoh[43], K. Terashi[86], J. Terron[54], S. Terzo[143], M. Testa[75], R. J. Teuscher[7,244], S. J. Thais[102], N. Themistokleous[165], T. Theveneaux-Pelzer[59], F. Thiele[8], D. W. Thomas[6], J. O. Thomas[136], J. P. Thomas[49], E. A. Thompson[59], P. D. Thompson[49], E. Thomson[171], E. J. Thorpe[137], R. E. Ticse Torres[5], V. O. Tikhomirov[37,269], Yu. A. Tikhonov[72,71], S. Timoshenko[131], P. Tipton[102], S. Tisserant[1], K. Todome[39,38], S. Todorova-Nova[163], S. Todt[134], J. Tojo[221], S. Tokár[92], K. Tokushuku[78], E. Tolley[147], R. Tombs[121], K. G. Tomiwa[176], M. Tomoto[78,84], L. Tompkins[115], P. Tornambe[3], E. Torrence[48], H. Torres[134], E. Torró Pastor[79], M. Toscani[187], C. Tosciri[56], J. Toth[1,270], D. R. Tovey[61], A. Traeet[154], C. J. Treado[184], T. Trefzger[138], F. Tresoldi[9], A. Tricoli[91], I. M. Trigger[164], S. Trincaz-Duvoid[124], D. A. Trischuk[183], W. Trischuk[7], B. Trocmé[181], A. Trofymov[24], C. Troncon[47], F. Trovato[9], L. Truong[148], M. Trzebinski[100], A. Trzupek[100], F. Tsai[59], J. C.-L. Tseng[56], P. V. Tsiareshka[213,258], A. Tsirigotis[98,259], V. Tsiskaridze[129], E. G. Tskhadadze[219], M. Tsopoulou[98], I. I. Tsukerman[204], V. Tsulaia[32], S. Tsuno[78], D. Tsybychev[129], Y. Tu[227], A. Tudorache[41], V. Tudorache[41], T. T. Tulbure[232], A. N. Tuna[88], S. Turchikhin[30], D. Turgeman[106], I. Turk Cakir[223,271], R. J. Turner[49], R. Turra[47], P. M. Tuts[70], S. Tzamarias[98], E. Tzovara[15], K. Uchida[86], F. Ukegawa[212], G. Unal[4], M. Unal[63], A. Undrus[91], G. Unel[76], F. C. Ungaro[110], Y. Unno[78], K. Uno[86], J. Urban[153], P. Urquijo[110], G. Usai[104], Z. Uysal[127], V. Vacek[44], B. Vachon[31], K. O. H. Vadla[142], T. Vafeiadis[4], A. Vaidya[113], C. Valderanis[19], E. Valdes Santurio[65,66], M. Valente[164], S. Valentinetti[39,38], A. Valero[79], L. Valéry[59], R. A. Vallance[49], A. Vallier[4], J. A. Valls Ferrer[79], T. R. Van Daalen[143], P. Van Gemmeren[12], S. Van Stroud[113], I. Van Vulpen[43], M. Vanadia[33,34], W. Vandelli[4], M. Vandenbroucke[62], E. R. Vandewall[74], A. Vaniachine[46], D. Vannicola[77,99], R. Vari[77], E. W. Varnes[133], C. Varni[112,111], T. Varol[45], D. Varouchas[24], K. E. Varvell[105], M. E. Vasile[41], G. A. Vasquez[40], F. Vazeille[25], D. Vazquez Furelos[143], T. Vazquez Schroeder[4], J. Veatch[5], V. Vecchio[135], M. J. Veen[43], L. M. Veloce[7], F. Veloso[28,198], S. Veneziano[77], A. Ventura[175,207], A. Verbytskyi[114], V. Vercesi[195], M. Verducci[73,139], C. M. Vergel Infante[60], C. Vergis[108], W. Verkerke[43], A. T. Vermeulen[43], J. C. Vermeulen[43], C. Vernieri[115], P. J. Verschuuren[6], M. C. Vetterli[101], N. Viaux Maira[152], T. Vickey[61], O. E. Vickey Boeriu[61], G. H. A. Viehhauser[56], L. Vigani[144], M. Villa[39,38], M. Villaplana Perez[141], E. M. Villhauer[165], E. Vilucchi[75], M. G. Vincter[130], G. S. Virdee[49], A. Vishwakarma[165], C. Vittori[39,38], I. Vivarelli[9], M. Vogel[96], P. Vokac[44], S. E. von Buddenbrock[176], E. Von Toerne[108], V. Vorobel[163], K. Vorobev[131], M. Vos[79], J. H. Vossebeld[145], M. Vozak[135], N. Vranjes[103], M. Vranjes Milosavljevic[103], V. Vrba[44,273], M. Vreeswijk[43], N. K. Vu[1], R. Vuillermet[4], I. Vukotic[203], S. Wada[212], P. Wagner[108], W. Wagner[96], J. Wagner-Kuhr[19], S. Wahdan[96], H. Wahlberg[52], R. Wakasa[212], V. M. Walbrecht[114], J. Walder[22], R. Walker[19], S. D. Walker[6], W. Walkowiak[122], V. Wallangen[65,66], A. M. Wang[88], A. Z. Wang[109], C. Wang[116], C. Wang[149], F. Wang[109], H. Wang[32], H. Wang[141], J. Wang[173], P. Wang[136], Q. Wang[2], R.-J. Wang[15], R. Wang[116], R. Wang[12], S. M. Wang[45], W. T. Wang[116], W. Wang[170], W. X. Wang[116], Y. Wang[116], Z. Wang[58], C. Wanotayaroj[59], A. Warburton[31], C. P. Ward[121], R. J. Ward[49], N. Warrack[119], A. T. Watson[49], M. F. Watson[49], G. Watts[53], B. M. Waugh[113], A. F. Webb[63], C. Weber[91], M. S. Weber[64], S. A. Weber[130], S. M. Weber[68],

A. R. Weidberg[56], J. Weingarten[186], M. Weirich[15], C. Weiser[83], P. S. Wells[4], T. Wenaus[91], B. Wendland[186], T. Wengler[4], S. Wenig[4], N. Wermes[108], M. Wessels[68], T. D. Weston[64], K. Whalen[48], A. M. Wharton[118], A. S. White[58], A. White[104], M. J. White[192], D. Whiteson[76], B. W. Whitmore[118], W. Wiedenmann[109], C. Wiel[134], M. Wielers[22], N. Wieseotte[15], C. Wiglesworth[8], L. A. M. Wiik-Fuchs[83], H. G. Wilkens[4], L. J. Wilkins[6], H. H. Williams[171], S. Williams[121], S. Willocq[3], P. J. Windischhofer[56], I. Wingerter-Seez[16], E. Winkels[9], F. Winklmeier[48], B. T. Winter[83], M. Wittgen[115], M. Wobisch[236], A. Wolf[15], R. Wölker[56], J. Wollrath[83], M. W. Wolter[100], H. Wolters[28,198], V. W. S. Wong[183], N. L. Woods[23], S. D. Worm[59], B. K. Wosiek[100], K. W. Woźniak[100], K. Wraight[119], S. L. Wu[109], X. Wu[21], Y. Wu[116], J. Wuerzinger[56], T. R. Wyatt[135], B. M. Wynne[165], S. Xella[8], J. Xiang[226], X. Xiao[58], X. Xie[116], I. Xiotidis[9], D. Xu[97], H. Xu[116], H. Xu[116], L. Xu[91], T. Xu[62], W. Xu[58], Y. Xu[172], Z. Xu[185], Z. Xu[115], B. Yabsley[105], S. Yacoob[93], D. P. Yallup[113], N. Yamaguchi[221], Y. Yamaguchi[87], A. Yamamoto[78], M. Yamatani[86], T. Yamazaki[86], Y. Yamazaki[215], J. Yan[149], Z. Yan[155], H. J. Yang[149,150], H. T. Yang[32], S. Yang[116], T. Yang[226], X. Yang[185,181], Y. Yang[86], Z. Yang[116], W.-M. Yao[32], Y. C. Yap[59], E. Yatsenko[149], H. Ye[170], J. Ye[136], S. Ye[91], I. Yeletskikh[30], M. R. Yexley[118], E. Yigitbasi[155], P. Yin[70], K. Yorita[220], K. Yoshihara[60], C. J. S. Young[4], C. Young[115], J. Yu[60], R. Yuan[185,272], X. Yue[68], M. Zaazoua[120], B. Zabinski[100], G. Zacharis[42], E. Zaffaroni[21], J. Zahreddine[124], A. M. Zaitsev[146,241], T. Zakareishvili[169], N. Zakharchuk[130], S. Zambito[4], D. Zanzi[4], S. V. Zeißner[186], C. Zeitnitz[96], G. Zemaityte[56], J. C. Zeng[94], O. Zenin[146], T. Ženiš[92], D. Zerwas[24], M. Zgubič[56], B. Zhang[170], D. F. Zhang[172], G. Zhang[172], J. Zhang[12], K. Zhang[97], L. Zhang[170], L. Zhang[116], M. Zhang[94], R. Zhang[109], S. Zhang[58], X. Zhang[149], X. Zhang[185], Y. Zhang[97,177], Z. Zhang[173], Z. Zhang[24], P. Zhao[81], Z. Zhao[116], A. Zhemchugov[30], Z. Zheng[58], D. Zhong[94], B. Zhou[58], C. Zhou[109], H. Zhou[133], M. S. Zhou[97,177], M. Zhou[129], N. Zhou[149], Y. Zhou[133], C. G. Zhu[185], C. Zhu[97,177], H. L. Zhu[116], H. Zhu[97], J. Zhu[58], Y. Zhu[116], X. Zhuang[97], K. Zhukov[37], V. Zhulanov[72,71], D. Zieminska[158], N. I. Zimine[30], S. Zimmermann[83,273], Z. Zinonos[114], M. Ziolkowski[122], L. Živković[103], G. Zobernig[109], A. Zoccoli[39,38], K. Zoch[5], T. G. Zorbas[61], R. Zou[203] and L. Zwalinski[4]

[1]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France. [2]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, USA. [3]Department of Physics, University of Massachusetts, Amherst, MA, USA. [4]CERN, Geneva, Switzerland. [5]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany. [6]Department of Physics, Royal Holloway University of London, Egham, UK. [7]Department of Physics, University of Toronto, Toronto, Ontario, Canada. [8]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark. [9]Department of Physics and Astronomy, University of Sussex, Brighton, UK. [10]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel. [11]Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel. [12]High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA. [13]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy. [14]ICTP, Trieste, Italy. [15]Institut für Physik, Universität Mainz, Mainz, Germany. [16]LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France. [17]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland. [18]Department of Physics, Northern Illinois University, DeKalb, IL, USA. [19]Fakultät für Physik, Ludwig-Maximilians-Universität München, Munich, Germany. [20]Department of Physics, Bogazici University, Istanbul, Turkey. [21]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland. [22]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK. [23]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA. [24]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France. [25]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France. [26]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands. [27]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania. [28]Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisbon, Portugal. [29]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain. [30]Joint Institute for Nuclear Research, Dubna, Russia. [31]Department of Physics, McGill University, Montreal, Quebec, Canada. [32]Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, USA. [33]INFN Sezione di Roma Tor Vergata, Rome, Italy. [34]Dipartimento di Fisica, Università di Roma Tor Vergata, Rome, Italy. [35]Faculty of Science, Kyoto University, Kyoto, Japan. [36]Fysiska Institutionen, Lunds Universitet, Lund, Sweden. [37]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia. [38]Dipartimento di Fisica, INFN Bologna and Università di Bologna, Bologna, Italy. [39]INFN Sezione di Bologna, Bologna, Italy. [40]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada. [41]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania. [42]Physics Department, National Technical University of Athens, Zografou, Greece. [43]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands. [44]Czech Technical University in Prague, Prague, Czech Republic. [45]Institute of Physics, Academia Sinica, Taipei, Taiwan. [46]Tomsk State University, Tomsk, Russia. [47]INFN Sezione di Milano, Milan, Italy. [48]Institute for Fundamental Science, University of Oregon, Eugene, OR, USA. [49]School of Physics and Astronomy, University of Birmingham, Birmingham, UK. [50]INFN Sezione di Napoli, Naples, Italy. [51]Dipartimento di Fisica, Università di Napoli, Naples, Italy. [52]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina. [53]Department of Physics, University of Washington, Seattle, WA, USA. [54]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain. [55]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil. [56]Department of Physics, Oxford University, Oxford, UK. [57]Department of Physics, Brandeis University, Waltham, MA, USA. [58]Department of Physics, University of Michigan, Ann Arbor, MI, USA. [59]Deutsches Elektronen-Synchrotron DESY,

Hamburg and Zeuthen, Germany. [60]Department of Physics and Astronomy, Iowa State University, Ames, IA, USA. [61]Department of Physics and Astronomy, University of Sheffield, Sheffield, UK. [62]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France. [63]Department of Physics, University of Texas at Austin, Austin, TX, USA. [64]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland. [65]Department of Physics, Stockholm University, Stockholm, Sweden. [66]Oskar Klein Centre, Stockholm, Sweden. [67]Dipartimento di Fisica, Università di Milano, Milan, Italy. [68]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany. [69]Physics Department, National and Kapodistrian University of Athens, Athens, Greece. [70]Nevis Laboratory, Columbia University, Irvington, NY, USA. [71]Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia. [72]Novosibirsk State University Novosibirsk, Novosibirsk, Russia. [73]INFN Sezione di Pisa, Pisa, Italy. [74]Department of Physics, Oklahoma State University, Stillwater, OK, USA. [75]INFN e Laboratori Nazionali di Frascati, Frascati, Italy. [76]Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA. [77]INFN Sezione di Roma, Rome, Italy. [78]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan. [79]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia, Spain. [80]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil. [81]Department of Physics, Duke University, Durham, NC, USA. [82]Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada. [83]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany. [84]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan. [85]Ochanomizu University, Tokyo, Japan. [86]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan. [87]Department of Physics, Tokyo Institute of Technology, Tokyo, Japan. [88]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, USA. [89]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden. [90]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco. [91]Physics Department, Brookhaven National Laboratory, Upton, NY, USA. [92]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia. [93]Department of Physics, University of Cape Town, Cape Town, South Africa. [94]Department of Physics, University of Illinois, Urbana, IL, USA. [95]Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany. [96]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany. [97]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China. [98]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece. [99]Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy. [100]Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland. [101]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada. [102]Department of Physics, Yale University, New Haven, CT, USA. [103]Institute of Physics, University of Belgrade, Belgrade, Serbia. [104]Department of Physics, University of Texas at Arlington, Arlington, TX, USA. [105]School of Physics, University of Sydney, Sydney, Australia. [106]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel. [107]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, USA. [108]Physikalisches Institut, Universität Bonn, Bonn, Germany. [109]Department of Physics, University of Wisconsin, Madison, WI, USA. [110]School of Physics, University of Melbourne, Melbourne, Victoria, Australia. [111]Dipartimento di Fisica, Università di Genova, Genova, Italy. [112]INFN Sezione di Genova, Genova, Italy. [113]Department of Physics and Astronomy, University College London, London, UK. [114]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany. [115]SLAC National Accelerator Laboratory, Stanford, CA, USA. [116]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China. [117]Konstantinov Nuclear Physics Institute of National Research Centre 'Kurchatov Institute', PNPI, St Petersburg, Russia. [118]Physics Department, Lancaster University, Lancaster, UK. [119]SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, UK. [120]Faculté des Sciences, Université Mohammed V, Rabat, Morocco. [121]Cavendish Laboratory, University of Cambridge, Cambridge, UK. [122]Department Physik, Universität Siegen, Siegen, Germany. [123]California State University, Long Beach, CA, USA. [124]LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France. [125]Department of Physics and Astronomy, Tufts University, Medford, MA, USA. [126]Department of Physics, University of Warwick, Coventry, UK. [127]Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey. [128]Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey. [129]Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA. [130]Department of Physics, Carleton University, Ottawa, Ontario, Canada. [131]National Research Nuclear University MEPhI, Moscow, Russia. [132]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca, Morocco. [133]Department of Physics, University of Arizona, Tucson, AZ, USA. [134]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany. [135]School of Physics and Astronomy, University of Manchester, Manchester, UK. [136]Physics Department, Southern Methodist University, Dallas, TX, USA. [137]School of Physics and Astronomy, Queen Mary University of London, London, UK. [138]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany. [139]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy. [140]INFN Sezione di Roma Tre, Rome, Italy. [141]Department of Physics, University of Alberta, Edmonton, Alberta, Canada. [142]Department of Physics, University of Oslo, Oslo, Norway. [143]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain. [144]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany. [145]Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK. [146]Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia. [147]Ohio State University, Columbus, OH, USA. [148]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa. [149]School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China. [150]Tsung-Dao Lee Institute, Shanghai, China. [151]Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA. [152]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile. [153]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic. [154]Department for Physics and Technology, University of Bergen, Bergen, Norway. [155]Department of Physics, Boston University, Boston, MA, USA. [156]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany. [157]Department of Physics, Ankara University, Ankara, Turkey. [158]Department of Physics, Indiana University, Bloomington, IN, USA. [159]Dipartimento di Matematica e Fisica, Università Roma Tre, Rome, Italy. [160]University of Iowa, Iowa City, IA, USA. [161]Dipartimento di Fisica, Università della Calabria, Rende, Italy. [162]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy. [163]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic. [164]TRIUMF, Vancouver, British Columbia, Canada. [165]SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK. [166]Departamento de Física, Universidade do Minho, Braga, Portugal. [167]Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey. [168]Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic. [169]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia. [170]Department of Physics, Nanjing University, Nanjing, China. [171]Department of Physics, University of Pennsylvania, Philadelphia, PA, USA. [172]Physics Department, Tsinghua University, Beijing, China. [173]Department of Physics, Chinese University of Hong Kong, Shatin, Hong Kong. [174]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan. [175]INFN Sezione di Lecce, Lecce, Italy. [176]School of Physics, University of the Witwatersrand, Johannesburg, South Africa. [177]University of Chinese Academy of Science (UCAS), Beijing, China. [178]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic. [179]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia. [180]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy. [181]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble, France. [182]Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal. [183]Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada. [184]Department of Physics, New York University, New York, NY, USA. [185]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China. [186]Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany. [187]Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina. [188]Department of Physics and Astronomy, York University, Toronto, Ontario, Canada. [189]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile. [190]Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil. [191]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil.

[192]Department of Physics, University of Adelaide, Adelaide, South Australia, Australia. [193]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal. [194]National Centre for Scientific Research 'Demokritos', Agia Paraskevi, Greece. [195]INFN Sezione di Pavia, Pavia, Italy. [196]Dipartimento di Fisica, Università di Pavia, Pavia, Italy. [197]Physics Department, University of Texas at Dallas, Richardson, TX, USA. [198]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal. [199]INFN-TIFPA, Trento, Italy. [200]Università degli Studi di Trento, Trento, Italy. [201]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan. [202]Nagasaki Institute of Applied Science, Nagasaki, Japan. [203]Enrico Fermi Institute, University of Chicago, Chicago, IL, USA. [204]Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre 'Kurchatov Institute', Moscow, Russia. [205]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland. [206]D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia. [207]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy. [208]Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco. [209]West University in Timisoara, Timisoara, Romania. [210]Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA. [211]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria. [212]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan. [213]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus. [214]Department of Physics, Shinshu University, Nagano, Japan. [215]Graduate School of Science, Kobe University, Kobe, Japan. [216]Graduate School of Science, Osaka University, Osaka, Japan. [217]Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus. [218]Physics Department, SUNY Albany, Albany, NY, USA. [219]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia. [220]Waseda University, Tokyo, Japan. [221]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan. [222]Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. [223]Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey. [224]Department of Physics, Universidad Andres Bello, Santiago, Chile. [225]Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile. [226]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong. [227]Department of Physics, University of Hong Kong, Hong Kong, China. [228]Physics Department, Royal Institute of Technology, Stockholm, Sweden. [229]Centro de Física Nuclear da Universidade de Lisboa, Lisbon, Portugal. [230]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia. [231]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan. [232]Transilvania University of Brasov, Brasov, Romania. [233]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania. [234]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France. [235]Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia. [236]Louisiana Tech University, Ruston, LA, USA. [237]Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey. [238]Kyoto University of Education, Kyoto, Japan. [239]Present address: Department of Physics, University of Fribourg, Fribourg, Switzerland. [240]Present address: Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain. [241]Present address: Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia. [242]Present address: Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel. [243]Present address: Università di Napoli Parthenope, Naples, Italy. [244]Present address: Institute of Particle Physics (IPP), Victoria, British Columbia, Canada. [245]Present address: Department of Physics, St Petersburg State Polytechnical University, St Petersburg, Russia. [246]Present address: Borough of Manhattan Community College, City University of New York, New York, NY, USA. [247]Present address: Department of Physics, California State University, Fresno, CA, USA. [248]Present address: Department of Financial and Management Engineering, University of the Aegean, Chios, Greece. [249]Present address: Centro Studi e Ricerche Enrico Fermi, Rome, Italy. [250]Present address: Department of Physics, California State University, East Bay, CA, USA. [251]Present address: Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain. [252]Present address: Graduate School of Science, Osaka University, Osaka, Japan. [253]Present address: Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany. [254]Present address: University of Chinese Academy of Sciences (UCAS), Beijing, China. [255]Present address: Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan. [256]Present address: Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands. [257]Present address: CERN, Geneva, Switzerland. [258]Present address: Joint Institute for Nuclear Research, Dubna, Russia. [259]Present address: Hellenic Open University, Patras, Greece. [260]Present address: The City College of New York, New York, NY, USA. [261]Present address: Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine, Italy. [262]Present address: Department of Physics, California State University, Sacramento, CA, USA. [263]Present address: Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland. [264]Present address: Louisiana Tech University, Ruston, LA, USA. [265]Present address: Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria. [266]Present address: Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia. [267]Present address: Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany. [268]Present address: CPPM, Aix-Marseille Université, Marseille, France. [269]Present address: National Research Nuclear University MEPhI, Moscow, Russia. [270]Present address: Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary. [271]Present address: Giresun University, Faculty of Engineering, Giresun, Turkey. [272]Present address: Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA. [273]Deceased: F. Bauer, O. Igonkina, D. Lellouch, A. Ouraou, V. Vrba, S. Zimmermann. ✉e-mail: atlas.publications@cern.ch